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THE LAVAS OF THE MODOC LAVA-BED QUADRANGLE, CALIFORNIA

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ABSTRACT

The Modoc Lava-Bed quadrangle includes an area in which is seen the transition from the Cascade Mountain province to the Great Basin plateau province, with mountains of volcanic accumulation (dissected and undissected) characteristic of the former, and fault-block mountains and high plateaus, typical of the latter.

The oldest volcanic rocks, the Cedarville andesite of Miocene age, are a series of pyroclastic formations, with a few interbedded flows, chiefly andesitic. After warping and the development of fault blocks, renewed volcanic activity built several volcanic cones from massive lava flows, chiefly andesitic, called the Massive Lava Group. These eruptions are correlated with the major Cascade activity of Pliocene age.

Lake beds (Lacustrine group) and widespread flows of olivine basalt (Warner basalt) were deposited in the grabens. In late Pleistocene time, the lavas of the Platy Andesite Group were erupted from a number of vents located on a fracture zone which encircled the top of one of the Pliocene volcanoes. New fault-grabens were formed and further lacustrine deposition took place. In post-Glacial time the Modoc basalts were erupted from a number of parasitic vents on the north and south flanks of the Medicine Lake Highland, the last flow is probably less than 500 years old. During this basaltic activity, several small eruptions of dacite and rhyolite took place on the top of the Medicine Lake Highland; the youngest rhyolite is probably less than 300 years old.

Many of the basalts of the area are abnormally rich in olivine and calcic plagioclase, thus resembling the Porphyritic Central Magma Type of Mull; but they were, in contrast, completely liquid at the time of extrusion.

In attempting to explain the difference in composition between several pairs of associated lavas by fractional crystallization, it was found that the residual liquid after partial crystallization of the less siliceous magma was richer in iron than the more siliceous rock of the pair.

In a partly glassy basalt the pyroxene and iron oxide had not begun to crystallize though over half of the plagioclase had formed crystals. The texture of the basalts suggests that pigeonite is a late-forming mineral in less siliceous basalts which crystallize with ophitic or sub-ophitic texture; and hypersthene and augite are early-forming minerals in more siliceous basalts and andesites which crystallize with intergranular texture.

The abnormally high lime content of the plagioclase phenocrysts of the Lake basalt may be explained with no less difficulty by assuming that the composition

of the liquid surrounding the phenocrysts was changed, than by assuming movement of the crystals from one liquid to another.

Strange globular bodies, found in the vesicular phase of both dacite and rhyolite flows, may represent a liquid fraction, high in volatile constituents, and with the silicate composition approaching Vogt's anchi-eutectic granite, which separated as an immiscible liquid from the dryer lava of the flows.

CONTENTS

INTRODUCTION.....	254
PHYSICAL FEATURES.....	256
GEOLOGY AND PETROGRAPHY.....	257
General Statement.....	257
Pre-volcanic Rocks.....	258
Cedarville Andesite.....	258
Massive Lava Group.....	259
Basalt of Bear Mountain.....	260
Tridymite Dacite of Haight Mountain.....	261
Andesite of Garner Mountain.....	261
Basalt near Medicine Lake.....	262
Rhyolite.....	264
Lacustrine Beds.....	266
Warner Basalt.....	266
Platy Andesite Group.....	269
Pyroxene Andesite.....	270
Rhyolite.....	271
Dacite.....	272
Modoc Basalt.....	272
Obsidian Group.....	275
Dacite.....	276
Rhyolite.....	278
Big Glass Mountain Complex.....	280
Pumice.....	281
PETROLOGY.....	282
Introduction.....	282
Basalts.....	282
Dacite and Rhyolite.....	288

INTRODUCTION

The Modoc Lava-bed quadrangle is located in northern California east of Mount Shasta and north of Lassen Peak (Fig. 1).

It has been mapped by the U. S. Geological Survey on a scale of 1/250,000 with a contour interval of 200 feet.

Although several geologists have visited this region, the literature contains very little information about it. J. S. Newberry¹ recorded a few general observations on the eastern part of the

¹ Newberry, J. S., *U. S. Pacific R. R. Expl.*, 33d Cong. 2d sess., Senate Ex. Doc. 78, vol. 13, pt. 6, 1856.

quadrangle. J. S. Diller² collected a specimen of obsidian near Medicine Lake which was analysed and described. The area is



FIG. 1. Map of northern California showing the location of Modoc Lava-bed Quadrangle.

mapped on the geological map of California by J. P. Smith³ but apparently from vague data. I. C. Russell⁴ and G. A. Waring⁵ in-

² Diller, J. S., *U. S. Geol. Survey Bull.* **148**, p. 228, 1897.

³ Smith, J. P., *Calif. St. Min. Bur. Bull.* **72**, 1916.

⁴ Russell, I. C., *U. S. Geol. Survey Bull.* **199**, 1902. *U. S. Geol. Survey Bull.* **217**, 1903. *U. S. Geol. Survey Bull.* **252**, 1905.

⁵ Waring, G. A., *U. S. Geol. Survey, W. S. Paper* **220**, 1908. *U. S. Geol. Survey, W. S. Paper* **231**, 1909.

clude the area in generalized statements about the extent of the plateau basalts of the Pacific northwest. R. J. Russell⁶ refers to the Recent lava flows of the Modoc country in his study of the Warner Range of northern California.

A study of the volcanic rocks of this area was sponsored by the Department of Mineralogy and Petrography of Harvard University. Dr. M. A. Peacock and the writer were sent into the field in the summer of 1927. Dr. Peacock's expenses were provided by his Commonwealth Fellowship and those of the writer were paid by Harvard University. During a two month's exploration the party prepared a reconnaissance geologic map using the Modoc Lava-bed quadrangle of the U. S. Geological Survey (scale 1/250,000) as a base and collected a large suite of rock specimens. In the fall of 1928, Dr. E. S. Larsen, Jr., of Harvard University, and the writer had the opportunity to check some of the earlier field observations during a three day trip through the area. The suite of rock specimens was studied by the writer in the Harvard Laboratories during the school years 1927-28 and 1928-29. A report of the study was accepted as a Doctor's dissertation by Harvard University in 1929. A general description of the area by M. A. Peacock was published in *The Geographical Review*, April 1931. The present report gives the geology and petrology of the lavas.

The writer wishes to express his appreciation to a number of persons for assistance in this work: Professor Charles Palache and Professor E. S. Larsen, Jr., constantly sponsored the entire study; Dr. E. S. Shepherd contributed five chemical analyses of rocks and offered many valuable suggestions; Professor R. A. Daly, Professor Kirk Bryan, Dr. C. S. Ross, and Dr. J. W. Greig were generous with helpful suggestions and criticisms.

PHYSICAL FEATURES

A volcanic highland, called here the "Medicine Lake Highland," is a prominent feature in the approximate center of the Modoc Lava-bed Quadrangle. Its highest point, Mt. Hoffman, is 8,018 feet above sea level. To the west, a series of volcanic peaks links this highland with the base of Mount Shasta. Another group of peaks lies to the southwest, with Grizzly Peak (elevation 6,804 feet)⁷ its highest member. At the southern base of Grizzly Peak, the

⁶ Russell, R. J., *Univ. of Calif. Publ. in Geol.* **17**, pp. 387-496, 1928.

⁷ These elevations from the reconnaissance survey of 1884-5 will probably be changed by the later surveys of the U. S. Forest Service.

Pit River has cut its canyon to an elevation of about 1,500 feet to give the maximum relief in the quadrangle. The physical features of this southwestern quarter of the area are typical of the Cascade Province. All of the peaks, with the exception of the Medicine Lake Highland, have rugged outlines produced by local Pleistocene glaciation and stream erosion. Medicine Lake Highland is a group of volcanic peaks which retain their original constructional slopes. These uneroded cones, however, are a superstructure on a volcanic dome which had been somewhat dissected previous to their eruption. The basalts of the Modoc Lava-beds form the northern and southern slopes of the Highland. In the northern and eastern parts of the quadrangle are a number of isolated peaks or groups of peaks which are dissected fault-blocks. Between them is a vast, undissected plateau ranging in elevation from 4,000 to 5,000 feet underlain by nearly horizontal basalt flows and lacustrine sediments. Here and there the plain is broken by cones of basaltic slag and by fault-scarps of Recent age.⁸ The plateau and fault-block area is physiographically like the Great Basin Province.

The study of the geology of the area was facilitated by the consistent relation between geology and topography in the field. The dissected fault-blocks are made up of bedded pyroclastic material with minor amounts of intruded and erupted lava, the Cedarville andesite. The other mountains in the area are made up of lava flows piled up around central vents. The extensive plateau is made up of widespread flows of basalt and a series of lacustrine sediments deposited both above and below the basalt horizon. These basalts have a wide distribution in northern California and Oregon and have been named the Warner basalt.

GEOLOGY AND PETROLOGY

GENERAL STATEMENT

Except for a small outcrop of older sandstone that crops out from beneath the volcanic rocks in the valley of Nelson Creek in the southwestern part of the quadrangle, all of the rocks of the area are Tertiary and Quaternary volcanic rocks and associated lacus-

⁸ The direction and location of the zones of Recent faults are shown on the reconnaissance geological map in solid lines; the zones of older faults in broken lines. No attempt was made to plot accurately each individual fault.

trine deposits. In Miocene time the earliest eruptions spread lava flows, and pyroclastic material, chiefly of andesitic composition, over a large area, and formed the Cedarville andesite. In the Pliocene renewed eruptions of andesites with some of basalt and rhyolite, from a number of separate vents, yielded the rocks of the massive lava group.

Fault blocks were formed chiefly displacing the Cedarville andesite and in the resulting lowlands in Pliocene or early Pleistocene time lacustrine beds and flows of basalt (Warner basalt) were spread. Beginning in late Pleistocene time and continuing to within a few hundred years of the present time, local eruptions took place from centers in the Medicine Lake Highland. These eruptions are from the earliest to the latest, the platy andesite, the Modoc basalt and cinder cones, and a number of eruptions from several centers of obsidian and pumice (Obsidian Group).

In quaternary time the Medicine Lake Highland was occupied by local glaciers.

PRE-VOLCANIC ROCKS

A bed of sandstone crops out beneath the volcanic series in the valley of Nelson Creek about a mile above its junction with the Pit River near the southwestern corner of the quadrangle. The rock is a coarse-grained, feldspathic, micaceous sandstone which shows no bedding and yielded no fossils. It must have been derived from granodiorite bodies exposed in some of the nearby mountains. The formation probably is a terrestrial deposit of early Tertiary age.

No other pre-volcanic rocks are exposed in the quadrangle, but the area is probably underlain by a basement of Jurassic metamorphics, Chico marine sediments, and early Tertiary terrestrial sediments comparable to the series described by Diller from the Pit River valley just south of the area.⁹

CEDARVILLE ANDESITES

The oldest series of volcanic rocks of the area was recognized in the field by the abundance of pyroclastic material, tilted and warped structure, and the gentle slopes eroded on its non-resistant pyroclastic members. The series shows great range in lithology:

⁹ Diller, J. S., *Bull. Geol. Soc. of Am.*, **4**, pp. 205-224, 1893. *U. S. Geol. Survey Geol. Atlas, Folio*, **15**, 1895.

basaltic flows, intrusives, and pyroclastics; andesitic flows and pyroclastics; and rhyolitic intrusives and pyroclastics. It may be correlated with the Cedarville Andesites of Miocene age in the Warner Mountains.¹⁰ Whether it represents both the Upper and Lower Cedarville or only one of them is not known. The flows and intrusives of basalt form cap rocks or resistant ledges and thus appear more abundant than they actually are. The basalt is typically dark gray to black and has a fine-grained, compact texture. Most of the specimens collected have the ophitic or intersertal texture common to the typical plateau basalt.¹¹ They are notable for the presence of chlorophaeite which is not found in the younger basalts of the area. A specimen of the basalt chosen for analysis—Table I, column 19141—contains pyroxene, olivine and labradorite in ophitic texture and a trace of chlorophaeite. A few of the basalts show an intergranular texture in which the pyroxene occurs in subhedral grains interstitial to the plagioclase tablets.

Andesitic members are most abundant in the series, and of these the pyroclastic rocks predominate. The lava specimens collected are all pyroxene andesites with both hypersthene and augite as phenocrysts. Fragments of hornblende andesite are found in detrital material.

Rhyolites are represented chiefly by beds of pumice-tuff. Fragments of pumice three to four inches in diameter are included in a matrix of smaller fragments of the same material. One dike of compact, reddish felsite was found which shows a brecciated border zone cemented by colorless to white opal. Local rumors of gold-bearing quartz veins may have originated in the discovery of some similar opalized dike.

MASSIVE LAVA GROUP

Following the Cedarville Andesite a group of massive basalts, andesites, and rhyolites were extruded from several vents. These rocks are readily distinguished by certain field characteristics. Their original flow surfaces have been removed by severe erosion. In the higher mountain peaks, the rock is exposed in rugged crags and barren rock-slopes. The flows are thick and massive with no

¹⁰ Russell, R. J., Basin Range Structure and Stratigraphy of the Warner Range, Northeastern California: *Univ. of Calif. Publ. in Geol.*, **17**, pp. 402-416, 1928.

¹¹ Washington, H. S., Deccan traps and other plateau basalts: *Bull. Geol. Soc. of Am.*, **33**, pp. 765-804, 1922.

platy or columnar jointing. On the lower slopes, most of the lava is covered by residual and washed soil and the few outcrops are small and uninformative. Pyroclastic members were not seen. The name Massive Lava Group is proposed for them from their massive character.

The exact geologic age of these lavas can not be determined. Severe glaciation of their outcrops shows that they are older than the Pleistocene. On the other hand, they do not seem to have been warped and faulted by the movements which modified the members of the Cedarville andesite. This would place them chronologically above the Miocene tuffs and below the glaciated surface. Probably their eruption was coincident with the major Pliocene activity which was widespread throughout the Cascade region.

The group is made up of several lithological types which occur in different parts of the area as follows:

Basalt of Bear Mountain, an even-grained olivine basalt.

Tridymite dacite of Haight Mountain, a hornblende-bearing hypersthene-tridymite dacite.

Andesite of Garnet Mountain, a hypersthene-augite andesite.

Basalt near Medicine Lake, a porphyritic olivine basalt.

Rhyolite.

Basalt of Bear Mountain. The olivine basalt of the Bear Mountain area is buried almost completely beneath a red, residual soil which supports a heavy growth of pine timber. The few outcrops consist of small exposures of massive rock which weathers into huge rounded boulders. Neither good columnar jointing nor marked flow-structure is apparent. The relation of the Bear Mountain rock to the lavas of the Grizzly Peak highlands is obscured in the soil-covered slopes of the McCloud and Bear Creek valleys. The contact of the basalt with the older Fort Mountain horst of Cedarville andesite also is located in a soil-covered lowland with no physiographic feature nor outcrop to indicate the relation of the two formations. On the northern and eastern sides, the basalt of Bear Mountain is covered by the Warner basalt. The two rocks are lithologically similar, but the basalts of the plateau show columnar jointing, vesicular surface phases, and a poor soil cover.

In hand-specimen, the Bear Mountain basalt is a light gray, loose-textured, uniform-grained rock, in which clear, yellow olivine grains are conspicuous in the network of colorless plagioclase crystals. In thin section, the type specimen is holocrystalline and contains about 60 per cent of plagioclase, 20 per cent of augite, 17

per cent of olivine, and 3 per cent of opaque ore. In texture and composition of minerals, the rock is similar to the Warner basalt.

An analysis of this rock is given in Table I, column 19071. It is almost a counterpart of the analyses of the basalts from the Cedarville andesite and the Warner basalt.

Tridymite Dacite of Haight Mountain. The only specimen of hornblende-bearing lava from the Massive Lava Group was collected from Haight Mountain. This peak is one of the highest in the area, and has been eroded most severely. It was dissected on the northeast side by a small alpine glacier and subsequently modified by normal stream erosion.

The rock is a light-colored porphyry in which dark-green prisms of hornblende and a few transparent plagioclase phenocrysts are conspicuous against a light, aphanitic ground mass. The hornblende phenocrysts make up four or five per cent of the rock. The phenocrysts are well-developed prismatic crystals of common hornblende, pleochroic in shades of green. Every individual is characterized by a thin reaction rim consisting mainly of magnetite dust and a small number of minute grains of monoclinic pyroxene. This reaction rim around intratelluric hornblende crystals is a common phenomenon in eruptive rocks. In many cases, as in the rock being described, the amount of reaction has been so slight that the form of the original crystal has not been destroyed. It is probably true that hornblende forms only if pressure on the system is sufficient to keep a considerable quantity of water in solution in the magma. If this amount of water is not held in solution, the hornblende becomes unstable and reacts with the magma. It is suggested that the common narrow reaction rim on intratelluric hornblende crystals is developed during the interval between the sudden loss of pressure in a magma system incident to the first breaking through to the surface and the final consolidation of the magma after its eruption as surface flows.

In addition to the hornblende, a few slightly-zoned, twinned, euhedral crystals of labradorite are present as phenocrysts. The ground mass is an intergranular growth of plagioclase tablets and hypersthene prisms with interstitial tridymite. The tridymite makes up about 20 per cent of the rock.

Andesite of Garner Mountain. The group of mountains west of the Medicine Lake Highland, of which Garner Mountain is the outstanding peak, was not studied in detail, but specimens taken from a number of scattered outcrops all proved to be closely re-

lated varieties of pyroxene andesite. Along the base of the steeper slopes, this andesite is covered by the later Plateau basalts. The contact of the Garner Mountain Andesite and the rock of Haight Mountain is located in the valleys of Antelope and Trout creeks and is obscured by a soil mantle.

In hand-specimen the rock is a dark-colored, fine-grained porphyry in which the glassy plagioclase phenocrysts are the only easily determined component. In thin-section the plagioclase phenocrysts make up about 30 per cent of the type specimen. They are notably twinned, show a number of recurrent zones, often include blebs of groundmass material, and have not been resorbed to any great extent. They range from one to five millimeters in the greatest dimension. The prismatic pyroxene phenocrysts, usually less than two millimeters long, make up about two per cent of the rock. About a third of these are augite and two thirds, hypersthene. The groundmass is an intersertal assemblage of small tablets of plagioclase (about 50 per cent), elongated prisms of hypersthene (about 15 per cent), irregular grains of opaque ore, and interstitial brown glass (about 30 per cent).

A chemical analysis of this rock is given in Table I, column 19145. The feldspar content is somewhat higher than that of the average Cascade andesite with similar silica percentage.

Basalt near Medicine Lake. The type locality for the "Lake" basalt is the eastern floor of the Medicine Lake basin where it crops out in low, glaciated mounds which protrude through a mantle of pumice and lake gravel covering the basin floor. The rock is also exposed in ledges which form the steep eastern shore of the lake. These outcrops consist of massive blocks of lava which apparently have been disarranged by ice-movement and give no clue as to the attitude of the lava flow.

This type area of the Lake basalt is completely surrounded by cinder cones and flows of younger platy andesite which form the rim of the lake basin and most of the upper slopes of the Medicine Lake Highland. On the northern and eastern slopes of the Highland, between the lower edges of the platy andesite flows and the younger basalts of the plateau, the Lake basalt is exposed in a number of scattered outcrops, of which some are small islands completely surrounded by the Warner basalt. The evidence is clear that both the Warner basalt and the platy andesite were poured out on a surface which had been eroded in the Lake basalt.

From this distribution of outcrops and relation of formations, it

is concluded that the early eruptions of Lake basalt piled up a broad volcanic dome. On top of this partly eroded dome, the superstructure of platy andesite cones was built, and the base of the resulting highland was buried beneath the flood of basalt which formed the plateau.

In hand-specimen, the type Lake basalt is a porphyry in which tabular crystals of glassy plagioclase, making up from 20 to 30 per cent of the bulk, stand out as phenocrysts in a loose-textured, light gray groundmass. Some of the plagioclase individuals are as much as 10 millimeters in length. A few scattered crystals of clear, yellow olivine are also visible as phenocrysts and form one per cent of the rock.

In thin-section, the plagioclase phenocrysts show a large central part (about eight-tenths of the volume of the average crystal) which has a uniform composition of ab15-an85. This slightly zoned core is surrounded by a narrow band of material which shows two significant zones (see Plate IIa). From the sharp break at the edge of the core, the anorthite content (indicated by extinction angle) decreases uniformly for a short distance. Then there is a distinct break in the gradation caused by a slight but abrupt drop in anorthite content. From this break, the plagioclase again gradually becomes poorer in anorthite to the outer edge of the phenocryst. The width of this zoned band seems to be about constant, regardless of the size of the central core. A few crystals which do not show the zoned border have irregular surfaces due to resorption. Most of them are so poorly twinned that it is impossible to compare accurately their composition with that of the crystals which do not show resorption. The last addition to the phenocrysts has about the same composition as the small plagioclase crystals in the groundmass, which are calcic andesine. The phenocrysts include an occasional grain of opaque ore, and some of them include small blebs of micro-aphanitic material which probably represents small amounts of magma trapped during the growth of the phenocrysts. These blebs are usually oriented along some crystallographic direction. A few long prisms of apatite are scattered through the plagioclase with no regard for crystallographic orientation. This lack of control suggests that the apatite formed after the crystallization of the plagioclase host.

The olivine phenocrysts are well-formed crystals about one millimeter in diameter which show no evidence of resorption but there is a suggestion of slight zoning on the edges of some of the crystals.

The optical constants give a composition of fay 23-for77 for the olivine.

The holocrystalline groundmass is an intergranular arrangement of tabular plagioclase, granular olivine, and prismatic pyroxene crystals, with about six per cent of opaque ore disseminated through the mass. The plagioclase crystals are slightly zoned, showing a constant decrease in anorthite from the center outward. Albitic twinning is prevalent, and extinction angles on the twins indicate an average composition of about an45. The olivine in the ground mass, about four per cent of the rock, occurs in small equant grains occupying spaces in the mesh of tabular plagioclase. Its composition is fay33-for67, 10 per cent more fayalite than is contained in the phenocrysts. The pyroxene makes up about 12 per cent of the rock, and is interstitial to the feldspar in grains so small that accurate determination of optical constants is impossible.

Two chemical analyses of the type specimen are given in Table I, columns 19144. The two chips which were analysed contained slightly different amounts of the plagioclase phenocrysts. Thus the two chemical analyses differ by amounts appropriate to this difference in mineralogical composition. The rock is extremely rich in the anorthite molecule, much of which, of course, is present in the plagioclase phenocrysts.

Rhyolite. Two rhyolitic flows were found in the Medicine Lake Highland which belong to the Massive Lava Group. One of them crops out in two small areas on the Davis Road about nine miles south of Pumice Stone Mountain, and the other is crossed by the road to Klamath Falls about 10 miles north of Medicine Lake. The northern flow was poured out on a slope which was comparable to the present northern slope of the Highland. The distribution of outcrops of the southern flow indicates that it also probably consolidated on a surface which sloped away from the present center of the Highland. The attitude of these two flows adds more evidence for the existence of a dome of Medicine Lake basalt as the foundation of the Medicine Lake Highland.

The rock forming the southern flow is an homogeneous black obsidian, occasionally banded with very fine layers of a lighter colored glass, and contains a few small, globular spherulites. The glass contains a few scattered acicular crystallites of feldspar, too small for determination, and a number of minute, lens-shaped bubble-holes. The feldspar crystallites and the bubble-holes are oriented

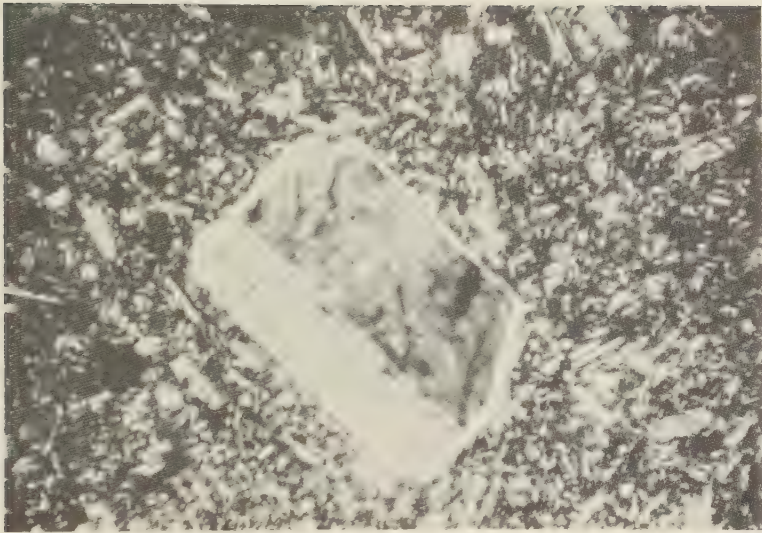


PLATE IIa. Photomicrograph, (x115) with crossed nicols, of a plagioclase phenocryst in the basalt of the Massive Lava Group near Medicine Lake, showing the large core of slightly zoned, calcic feldspar, and the narrow shell of highly zoned, more sodic feldspar.



PLATE IIb. Section in a platy andesite flow northwest of Medicine Lake showing the slightly glaciated surface, the vesicular upper phase about eight feet thick, and the inner platy phase of the flow. This exposure is a small Recent fault-scarp.

$\frac{1}{2}$



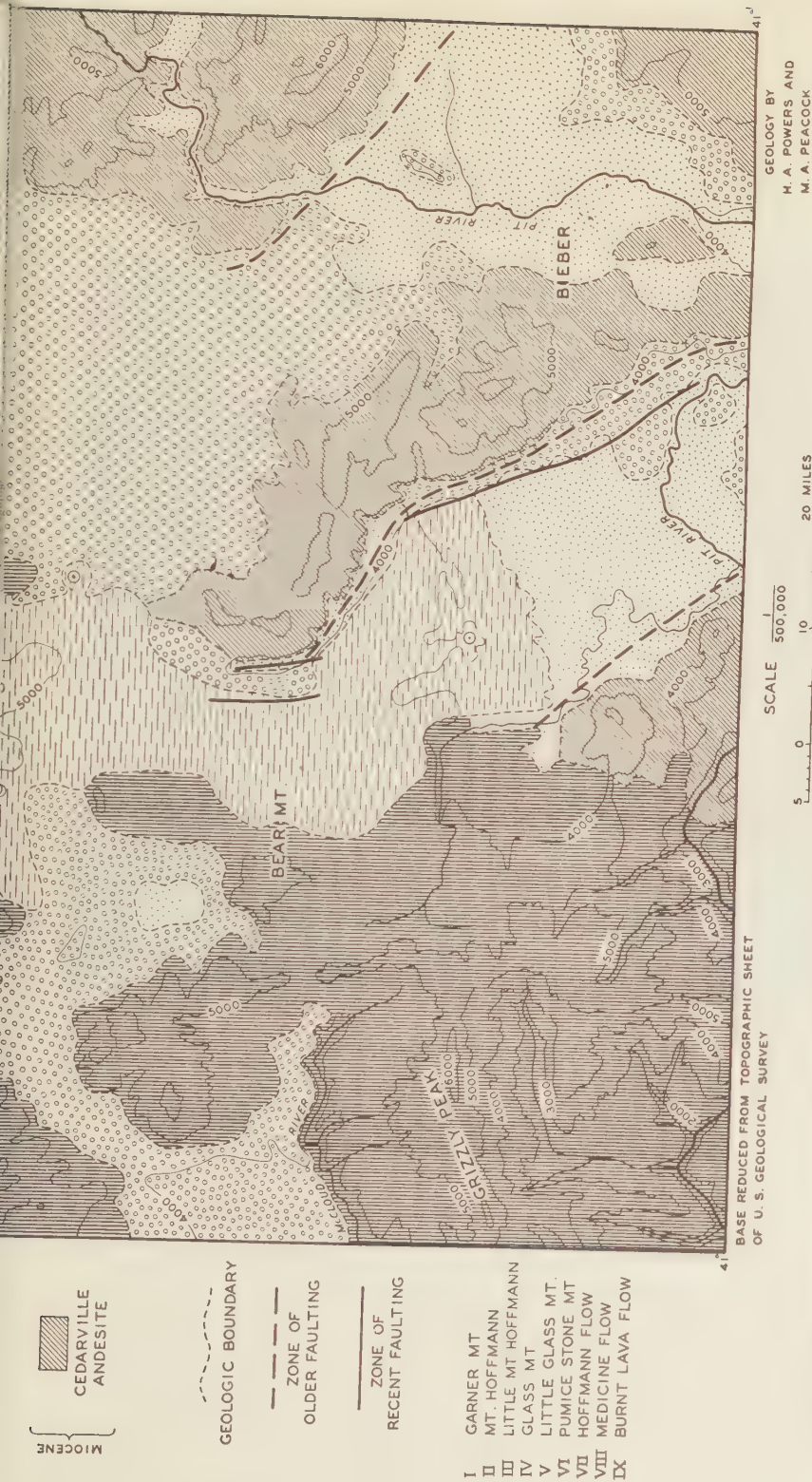


PLATE I. Geological reconnaissance map of Modoc Lava-Bed Quadrangle. Base map is U. S. Geol. Survey Modoc Lava-Bed Quadrangle. Geology by H. A. Powers and M. A. Peacock.



PLATE III. Aerial view of the recent cinder cone and the basaltic lava of Burnt Lava Flow southeast of Medicine Lake. The crater in the cone is about 80 feet deep. The lava has spread out in a comparatively smooth sheet surrounding the two older cinder cones. Photo, Brubaker Aerial Surveys, Portland, Oregon.

parallel to flow-bands which are made up of streaks of crystallites and an occasional crystal of oligoclase about .01 millimeter in length. The smaller crystallites form lines which bend around the few larger crystals. The flow-bands themselves are contorted. The growth of the crystallites must have taken place during the last stages of movement in the flow when viscosity was high enough to permit the preservation of the folded and contorted structures. The localization of a large part of the crystallization to these fine streaks was probably influenced by a local concentration of mineralizers. The index of refraction of the glass for sodium light is $1.4905 \pm .0005$ and its specific gravity is $2.36 \pm .01$. The chemical composition of the type specimen is given in Table I, column 19007.

The northern flow is composed of two textural varieties, a homogeneous glass and a finely-banded crystalline lithoidite. The glass forms the bottom of the flow and is several feet in thickness, though the upper and lower contacts of the glass were not visible. It is a stony-looking obsidian, with typical conchoidal fracture but a decidedly dull luster. Thin edges are semi-translucent and show a deep brown color. The rock is perfectly homogeneous and shows neither flow-structure nor spherulites. Microscopically it consists of a felt-like network of crystallites embedded in pure glass. A little opaque dust, probably magnetite, and an occasional minute prism of some indeterminable pyroxene are disseminated through the glass. The crystallites make up about 30 per cent of the rock, and interfere with an accurate determination of the refractive index. It was determined in white light to be $1.498 \pm .001$ and the specific gravity is $2.44 \pm .01$. The chemical composition is given in Table I, column 19044.

The crystalline facies is composed of thin bands of reddish, porous material alternating with dense, dark gray layers which have a glassy appearance. In thin-sections, the dense layers are composed of a felted mass of minute feldspar laths, including a few specks of hematite and a light green mineral probably a pyroxene. There is no glass visible. The porous layers are bounded by a narrow zone characterized by a concentration of hematite. They consist of slightly coarser crystals of feldspar and patches of tridymite, dusted with hematite specks. These layers probably represent small areas rich in volatile constituents which were drawn out into bands by movement of the flow. The presence of the volatiles favored the development of tridymite and of the larger feldspar crystals. The texture, while appearing typically rhyolitic in hand-specimen, is

seen to be truly trachytic with a complete absence of spherulitic or poikilitic intergrowths of feldspar and silica. A glimpse at the norm of this rock shows the presence of only 25 per cent of normative quartz which is to be expected in a rock with the trachytic texture, since it has been shown that siliceous lavas containing less than 26 per cent of normative quartz are characterized by trachytic texture.¹²

LACUSTRINE BEDS

After extensive block faulting of the Cedarville andesite, a great thickness of lake beds and basalts were deposited in the fault-graben depressions and built up widespread plateaus above which the upper parts of the upthrown blocks rose. The first sediments were deposited in large shallow lakes. They were covered by widespread flows of basalt. Recurrence of faulting¹³ then formed a number of small grabens in the basalt surface in which lake beds were formed by deposition which has continued to the present.

The Lacustrine beds are made up chiefly of silt, ash, and diatomaceous earth but include some minor deposits of fluviatile origin. The beds range in thickness from less than an inch to several feet. The sandy or ashy layers are more thinly bedded, while the diatomaceous members often consist of several feet of massive, structureless earth. No attempt was made to study the stratigraphy of the series.

WARNER BASALT

Nearly half of the surface of the quadrangle is underlain by these basalts. They may be traced eastward into the Alturas Quadrangle where Russell, calling them the Warner basalt, has described them as the most widespread unit in the area.¹⁴ To the north, much of the surface rock of the Oregon plateau east of the Cascade Range can be correlated with some assurance with the Warner basalt. The writer has travelled over the formation as far north as Bend, Oregon, and the rock is very constant in composition, form of occur-

¹² Powers, H. A., The relation of chemical composition to texture of ground mass in siliceous lavas: *Jour. Geol.*, **37**, pp. 268-71, 1929.

¹³ Two periods of faulting have been described also from the area just north of this quadrangle by Johnson and Gilbert:

Johnson, D. W., Block faulting on the Klamath Lake Region; *Jour. Geol.*, **26**, pp. 229-236, 1918.

Gilbert, G. K., Studies in Basin Range Structure; *U. S. Geol. Survey. Prof. Paper* **153**, 1928.

¹⁴ Russell, R. J. *Loc. cit.*, p. 416.

rence, and geological relations. As shown by Russell¹⁵, these are the basalts which have been correlated erroneously by Waring and J. P. Smith with the Miocene basalts of the Columbia River section.

In the Warner Mountain area, Russell found conformity between the Cedarville Series and the Warner basalt, and his greatest period of faulting is later than the Warner basalt.¹⁶ In the Modoc area, however, a major period of faulting followed the eruption of the Cedarville andesite and some erosion occurred before the pouring out of the Warner basalts. This lack of coincidence over a distance as small as 60 miles is in accord with the conception that the Great Basin faulting has reached its maximum development in different areas at different times.

The Warner Basalt is made up of a number of thin flows of basalt with great areal extent. In a fault-scarp west of Tule Lake a vertical section of 130 feet exposes 12 separate flows but does not show the bottom of the formation. The top and bottom flows are each at least 50 feet in thickness, two others are less than two feet thick and the other eight flows are from three to four feet thick. In a number of places where the total thickness of the series is exposed it is less than 50 feet. The formation probably averages a little over 100 feet in thickness.

The flows are almost universally vesicular at top and bottom, the upper vesicles being nearly spherical while the lower ones are usually pipe-like with the length of the pipe making a slight angle from the vertical in the direction of the flow-movement. Most of the flows show well-developed columnar jointing in which a five- or six-inch cross-section is most common. The flows have a pahoehoe type of surface which has been altered slightly by erosion.

The Warner basalt is a light gray, equi-granular loose textural rock with many honey-yellow olivine crystals and irregular grains of a greenish pyroxene disseminated through a feldspar matrix. The rock is remarkably constant in its composition and appearance over the whole area. Some 75 specimens were studied in thin-section and the texture and relative abundance of the various constituents is practically identical in all of them. The type specimen is coarse-grained for a basalt, the constituents having an average diameter of about one millimeter. The plagioclase is in slightly-zoned tablets. Monoclinic pyroxene fills the interstices between the other grains

¹⁵ *ibid.*, p. 417.

¹⁶ Russell, R. J., *Loc. cit.*, p. 422.

and often includes several crystals of plagioclase and olivine poikilitically. It has a purple-brown color in thin-section but is non-pleochroic. It has the following optical properties: $\alpha=1.693$; $\beta=1.701$; $\gamma=1.722$ (all $\pm .003$) $2V=53^\circ$. Using Winchell's diagrams these data indicate a pyroxene with about the following composition: Diopside 40, hedenbergite 45, clinoenstatite 15. About two per cent of opaque ore, probably magnetite, occurs in the pyroxene or along the boundaries between pyroxene and the other constituents. Rare specimens contain a few phenocrysts of calcic plagioclase which show much included groundmass material and no resorption nor recurrent zoning, so they probably were formed entirely in place in the flow. The chemical analysis is given in Table I, column 19123.

In the following table the composition of the plagioclase and olivine was determined from optical data, and the approximate composition of the pyroxene was computed from the rock analysis by subtracting the known amounts of plagioclase and olivine. The small amount of normative nephelite does not exist in the rock.

NORM		MODE		COMPOSITION MINERALS	
Or	0.0				
ab	17.8	plag.	60	ab 33—an 67	
an	40.0				
ne	0.8			FeSiO ₃	41
di	15.1	px.	15	MgSiO ₃	17
ol	24.0			CaSiO ₃	42
il	1.7				
ap	0.3	ol	23	fay 18—for 82	
		opaque	2		

The composition of the olivine and the pyroxene shows that the iron silicate molecule has been concentrated in the late-formed pyroxene. This concentration of iron in the residual liquid during the crystallization of basaltic magma has been discussed recently by Fenner,¹⁷ and the enrichment of late-formed pyroxene in clinoenstatite or clinohypersthene has been emphasized by Barth.¹⁸

¹⁷ Fenner, C. N. *Am. Jour. Sci.*, (5) **18**, 1929, pp. 225-53. Fenner, C. N. *Min. Mag.*, **22**, pp. 539-560, 1931.

¹⁸ Barth, T. F. W., *Am. Min.*, **16**, pp. 195-208, 1931.

PLATY ANDESITE GROUP

A group of lava flows with some cinder cones, made up predominately of pyroxene andesite characterized by a well developed platy jointing, and containing two small flows of rhyolite and a minor intrusive of dacite makes up most of the Medicine Lake Highland. The name platy andesite group is proposed for this group. The flows issued from a number of vents grouped around the top of the older volcano. Three recognizable vents are found in the ridge north of Medicine Lake, and four partly destroyed craters exist in the south ridge. The other peaks are more or less isolated cones. The structure of the cones and ridges is partly revealed by slight faulting on their slopes. Within the cones are small lava flows which dip in all directions away from each center of eruption, and the more extensive flows spread out radially from each vent.

These vents were grouped in such a manner on top of the old dome that the overlapping of the bases of the cones completely enclosed a large basin which is now partly occupied by Medicine Lake. On the topographic map, the lake basin with its encircling rim of ridges and cones suggests a partly dissected crater or caldera. The field evidence cited above reveals the error in this impression. However, the crude circular grouping of the platy andesite vents suggests fracturing around the circumference of the old crater, with subsequent minor eruptions along this circle of weakness. The area within this circular fault-zone may have subsided somewhat below its original position, with a tendency toward the formation of a caldera, but it could not have settled far because the old lava forms much of the floor of the lake basin upon which a number of the platy andesite flows were extruded. This subsidence, if any, played no great part in the formation of the present caldera-like topography which is due entirely to the arrangement of the centers of platy andesite eruption.

The original symmetrical shape of the cinder cones has been only slightly altered by erosion. One of the craters in the north ridge has been sufficiently well preserved to contain a small crater lake. The surface exposures of the flows themselves all show striations and ice polish but, in most cases, little more than a glassy surface slag has been removed. In one locality a small cirque has been cut in a flow at an elevation of about 6,600 feet, and several small cliffs have been formed by the plucking action of ice. On the whole, the flows have been modified by much less severe glacial

erosion than that which has carved out the rugged surfaces of the Massive Lava volcanoes at similar elevations.

In the chronological column, the Platy Andesite Group is located above the Massive Lava Group and below the Modoc Basalt Group. These relations are clearly established by field evidence. However, no locality was seen which showed the relation between the platy andesite and known Warner basalts. A few contacts of the two formations are shown on the map, but they were either obscured by soil or were located from a distance by topographic extrapolation. The available evidence indicates a Pleistocene age for the Platy andesite group.

Pyroxene Andesite. The most abundant rock of the Platy Andesite Group is the fine-grained pyroxene andesite which occurs in pyroclastic cones and widespread flows. Consolidation of the lava has yielded structures which are peculiar to the flows of this formation. The surface usually shows remnants of a black, highly vesicular, hypo-crystalline phase of unknown original thickness. By a decrease in size and number of vesicles, and an increase in crystallinity, this phase grades into a slightly vesicular, micro-crystalline, dark gray rock which shows no megascopic flow-structure. These two intergrading phases make up a surface layer, often as much as 20 feet thick, which is sharply separated from the main body of the flow. The inner part of each flow crystallized as a light gray, almost lavender, rock, with a very pronounced platy jointing parallel to the average flow-surface (see Plate IIb). The rock breaks along these joint-planes into flat slabs which average about an inch in thickness. In place, the rock has much the appearance of a bedded sediment. In hand-specimen, it is a fine-grained, feldspathic rock which rarely shows a few small phenocrysts of glassy plagioclase.

Microscopically the rock is composed of 65 to 70 per cent of minute tabular crystals (about .2 mm. long) of medium oligoclase arranged in definite trachytic texture and 10 to 15 per cent of minute prismatic crystals of pyroxene desseminated through the spaces between the plagioclase individuals. Most of the pyroxene is monoclinic, probably augite, but some appears to be hypersthene. A small amount of indeterminable crystalline material, probably excess silica and potash feldspar, fills the remaining spaces. In some specimens, especially from flow-surface phases, the interstitial material is glass. Small amounts of opaque oxide are dusted through the slides. One or two of the rocks show a few small grains of oli-

vine, and many of the rocks have an occasional phenocryst of medium andesine or hypersthene. In general, however, the different flows are remarkably uniform in composition and texture.

Cones of red cinders and slag have been built up over the vents. These vesicular phases show essentially the same mineral constituents and texture which characterize the flow-rock. The red color is caused by a cloud of minute flakes of hematite scattered through the rock. In slags which show flow-structure, the hematite is somewhat concentrated in irregular streaks which emphasize the flow-lines. The individual scales of hematite occur indiscriminately in feldspar pyroxene, or interstitial material, often crossing grain-boundaries, and show no individual orientation with the direction of flow-banding. It would seem, therefore, that they had been formed after crystallization and movement in the lava had ceased. Their origin may be due either to oxidation and concentration of the iron contained in the rock along planes accessible to invading oxidizing agents; to concentration of iron-bearing volatiles in the shear-planes of the rock during crystallization as discussed by Fuller;¹⁹ or even to an introduction of iron in an oxidizing medium from some source outside of the rock itself during the last fuming stage of the eruption. Textural evidence fits equally any one of these three possible modes of origin.

Two specimens from one of the flows were analysed, No. 19063, the platy phase and No. 19064 the vesicular surface phase. The two are practically identical, and are high in soda, iron oxides, and phosphorus relative to Lassen andesites with comparable silica content.

Rhyolite. There are two rhyolite flows; one on the inner slope of the west rim of Medicine Lake basin and the other partly surrounding the base of Mount Hoffmann. Both flows are almost completely buried beneath a cover of residual soil and late pumice drift. A small cirque is found in the flow on the inner side of the west rim of the basin, but even here the walls have broken down and exposures are poor. The readiness with which the rock breaks down may be attributed to the fact that the glass of both flows has been shattered by perlitic fracturing.

The material collected from both flows is of one type. In thin-section, the rock contains about 10 per cent of phenocrysts in a

¹⁹ Fuller, R. E., The mode of origin of the color of certain varicolored obsidians: *Jour. of Geol.*, **35**, p. 572. 1927.

glassy matrix. Most of the phenocrysts are zoned plagioclase crystals with a composition about sodic andesine. Some of them show evidence of resorption during a late stage in their development, though the last zone on all of them apparently was in equilibrium with the groundmass. A few crystals of angite and about two per cent hypersthene prisms are the remaining intratelluric minerals. The glass of the groundmass contains perhaps 20 per cent of minute plagioclase crystallites which are too small for accurate determination. The index of refraction of the glass is $1.493 \pm .0005$ for sodium light. No chemical analysis was made of this rock, but the index of the glass indicates a rhyolitic composition with about 72 per cent of silica. The perlitic cracks in the rock are all bounded by a narrow zone of indeterminable holocrystalline material in which are scattered a few flakes of hematite. This devitrification and formation of hematite were probably caused by moving solutions during the final stages of consolidation of the flows.

Dacite. The rock exposed at the top of Mount Hoffmann is a holocrystalline, light colored porphyry which probably was intruded in a cinder cone. Many small cavities in the rock are lined with botryoidal cristobalite. The thin section shows about 10 per cent of small, zoned plagioclase crystals (composition about medium andesine) and a few prisms of augite and hypersthene as phenocrysts in a holocrystalline groundmass. This is made up of a mat of minute tabular feldspar crystals and elongated hypersthene prisms contained in a matrix of indeterminable material which is dusted with small grains of opaque iron oxide. The interstitial material probably is a mixture of silica and alkali feldspar, so that mineral composition is that of a dacite or quartz latite.

MODOC BASALT

A group of Recent basalt eruptions began after the glaciation and continued to the present time. The youngest of these is certainly not over 500 years old. (See plates III and IVa.)

Very little chemical or mechanical decomposition has modified the surface of the flows. The meager amount of soil covering has been supplied by wind transportation of material from later pumice eruptions and from the exposed lake beds in the plateau. On the most recent of the flows, Burnt Lava Flow, only a few scattered pockets of pumice are found and most of the surface is unaltered lava. In the region just south and west of Tule Lake those basalts

lie in the graben's which were formed by the late faulting of the Warner basalt.

The name Modoc basalt is proposed for this group of flows. Most of the flows and cinder cones of the Modoc Basalt are found in two areas: one, the Modoc Lava beds on the northeast slope of the Medicine Lake Highland; the other, on the southern slope of the Highland. A few flows are scattered along the eastern and western flanks of the Highland, and a few eruptions took place at the top of the Highland in the vicinity of Medicine Lake. Little Mount Hoffmann is a Modoc basalt cone containing small, irregular intrusives, and several other small cinder cones were built on the platy andesite surface due north of Little Mount Hoffmann.

The eruption of the Modoc basalts was characterized by the formation of a great number of cinder cones. However, some flows issued from small fissure vents on the flanks of the Lake basalt. These sources are often marked by open throats which extend into the country rock at various angles. The road along the northern edge of Burnt Lava Flow passes almost over the mouth of one of the throats from which that flow was extruded.

The rock of most of the Modoc flows is dark gray, usually aphanitic, variably vesicular, and rarely visibly porphyritic. Locally, in surface slags and in the cinder cones, the iron of the rock has been oxidized, giving a brick-red color to the specimens. Thin-sections show that the red rocks have been impregnated with minute plates of hematite. The dissemination of the hematite, regardless of mineral-boundaries in the rock, and the field distribution of the oxidized material shows that the oxidation is of deuteric rather than atmospheric origin. Column 19086, Table I, gives the analysis of an oxidized cinder from a cone just west of Medicine Lake on the top of the Highland. Most of the iron is in the ferric state. The ratio of soda to potash is higher than in the other analysed Modoc basalts (see columns 19142, 19116, and 19143) and the total amount of phosphorus is higher. The vent from which this rock was erupted pierces an unknown thickness of the platy andesite, whereas the other analysed flows were not in contact with it so far as known from the field occurrence. The ratio of soda to potash and the total phosphorus is high in the platy andesite, so it may be that some assimilation of the platy andesite will account for these same characteristics in this particular flow of Modoc basalt.

The principal mineral constituents of the basalts are plagioclase, pyroxene, olivine, glass, and iron oxides. Plagioclase makes up from 45 to 55 per cent of the rocks in which its amount can be measured by the Rosiwal method, and varies in composition from medium labradorite to calcic andesine. Olivine ranges from zero to 20 per cent, and the pyroxene and glass vary antipathetically, either or both making up from 40 to 50 per cent of the rock. Most of the specimens show from 5 to 10 per cent of micro-phenocrysts (one millimeter) of labradorite and an occasional euhedral olivine crystal. The feldspar phenocrysts are slightly zoned and twinned, but do not show resorption or recurrent zoning. They often have included blebs of groundmass or small olivine crystals.

The texture of the rock differs considerably within definable limits. The most crystalline rocks range from ophitic types with late interstitial pyroxene to intergranular types with pyroxene prisms and plagioclase tablets of contemporaneous development. The least crystalline limit of texture is an intersertal arrangement of euhedral tablets of plagioclase, equant grains of olivine, and a mesostasis of brown glass dusted with iron oxide crystals. These partly glassy rocks may be an arrested stage of the development of either an ophitic or an intergranular holocrystalline type. Between the ophitic texture and the most glassy texture with no pyroxene are types which range from near-ophitic specimens with pyroxene in fibrous aggregates extinguishing in large units to near-glassy specimens in which the glass is replaced by a cryptocrystalline aggregate. In these the minute fibrous crystals are indeterminate but can be seen to be crystallographically parallel by their extinction positions.

The chemical composition of one of the holocrystalline ophitic rocks is given in Table I, column 19142. This rock shows 64 per cent of normative plagioclase, whereas a Rosiwal measurement shows only 45 per cent of plagioclase in the mode. The feldspar is too small for accurate determination, but its composition is about a sodic labradorite. The composition from the norm is a calcic labradorite, so without doubt some of the normative anorthite actually belongs in the pyroxene. This would reduce the per cent of normative plagioclase. Further, in a fine-grained rock, the Rosiwal determination invariably gives too high a percentage of the high index and opaque constituents. It is likely, therefore, that the rock actually contains about 55 per cent of plagioclase and 35 per cent of pyroxene.

One of the partly glassy rocks has the chemical composition given in Table I, column 19116. The norm shows too much plagioclase as in the other rock, though this glassy rock is slightly more siliceous and probably contains a little more feldspar than does the first one. The mode of the glassy rock shows 41 per cent of plagioclase, 44 per cent of glass (including the opaque ore) and 15 per cent of olivine. For the reason mentioned above, the amount of plagioclase probably should be higher at the expense of the glass. The norm of the rock shows only two per cent of olivine, while the mode shows nearly 15 per cent. If crystallization had continued slowly to completion, much of this early olivine would have been resorbed and would have reappeared as pyroxene, using silica which is included in the glass of the rock. Further, it is obvious that the 40 per cent of residual liquid, represented by the glass, is very much enriched in the iron metasilicate molecule and is relatively very low in feldspar, since the early olivine is rich in the forsterite molecule and since nearly three-fourths of the total feldspar of the rock has precipitated out of the liquid.

The intergranular texture is found in rocks which are so fine-grained that the mineral assemblage can not be studied in detail. Specimens from Burnt Lava Flow are good examples of this type. In thin-section, a few microphenocrysts of labradorite and olivine are disseminated through the intergranular groundmass of tabular plagioclase and grains of pyroxene. Both hypersthene and augite appear to be present but the grains are too small for accurate determination. An analysis, Table I, column 19143, shows that the composition of this type is intermediate between an ophitic basalt and a pyroxene andesite. The rock has quartz in the norm so the modal olivine can not be in equilibrium with the groundmass.

OBSIDIAN GROUP

Six different eruptions of lava and three separate pumice outbursts have occurred in Recent time within or near the circle of platy andesite vents on the top of the Medicine Lake Highland. Two extrusions of lava belong to an early episode, and the rest of the activity belongs to one grand display which took place so recently that it has a place in the legends of the Modoc Indians.²⁰ Since most of the rocks of this group are obsidians the name obsidian group will be applied to it.

²⁰ According to "Lava Jack" Stambaugh of Malin, Oregon, who has spent much of his life with the Modoc Indians.

"Medicine Flow" and "Hoffmann Flow," composed of dacitic lava, were erupted during the early activity. Both flows support a sparse growth of pines, though no soil has formed in place on their surfaces. Their age might be guessed as 800 or 1,000 years, with Hoffmann Flow slightly the older of the two.

Big Glass Mountain, Little Glass Mountain, and two small flows about a mile and a half northwest of Medicine Lake were formed during the later episode. Pumice cones were formed at vents which are closely associated with each of these centers of extrusion. Little Glass Mountain and the two small flows northwest of the lake are made up of rhyolitic obsidian. Big Glass Mountain is made up of lava varying in composition from rhyolite to dacite, with rhyolite in greatest abundance. All of these eruptions have occurred certainly within the last 500 years.

Dacite. Medicine Flow was extruded upon the comparatively level floor of the large lake basin between the north shore of Medicine Lake and the northern rim of platy andesite cones. The lava covers about one square mile and has a thickness of about 100 feet on the margins and 250 feet near the center. The thickest part of the flow probably marks the location of the vent from which the lava was extruded.

Hoffmann Flow occupies the floor of the northeast pass in the basin rim between Mount Hoffmann and Red Shale Butte. It has been partly buried by the later flows from Big Glass Mountain, so that the true size of the flow is unknown. The exposed area is a trifle less than that of Medicine Flow. The thickness at the western edge is about 75 feet, and the top of the flow rises slightly toward the east. The exact position of the vent is unknown, but apparently it lies to the east under the flows from Big Glass Mountain, and probably it coincides with the vent from which these later lavas were extruded.

The pine growth on Hoffmann Flow is rather more dense than that on Medicine Flow. With this exception, the two flows are identical in appearance. The flow fronts originally must have been nearly continuous walls of solid lava, varying from 50 to 100 feet high, standing with a slope considerably greater than that of the talus which has accumulated since movement ceased in the flows (see Plate IVb). The existing slope of the talus is even greater than the angle of repose for the heterogeneously-sized component blocks. Considered as a whole, the tops of the flows are compara-



PLATE IVa. Edge of Burnt Lava Flow showing the blocky, irregular detail of the surface as contrasted to its general smooth appearance in the aerial photo.



PLATE IVb. Margin of Medicine Flow, the dacite flow north of Medicine Lake. The flow front is about 150 feet high. Photo, M. A. Peacock.

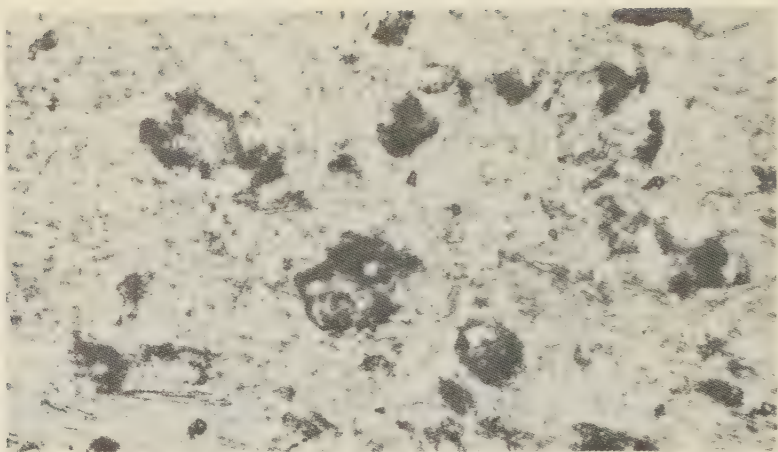


PLATE Va. Photomicrograph, (x115) with plane polarized light, of the dacite of Medicine Flow. The main groundmass contains many tabular plagioclase crystals, but the small globules are composed of finer crystals with none of the plagioclase tablets.

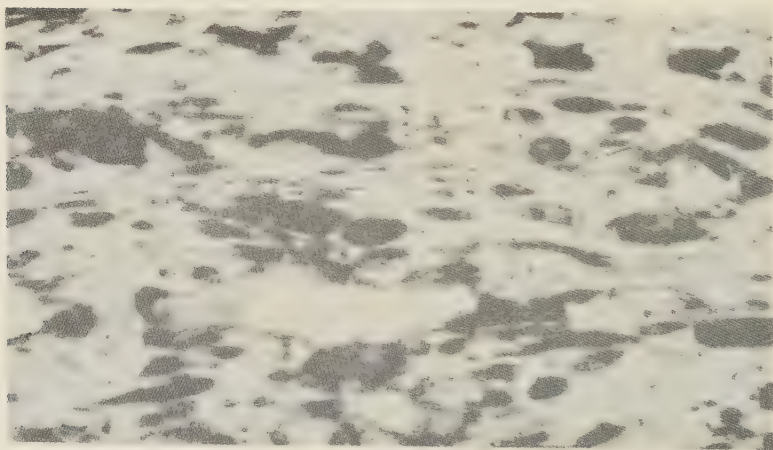


PLATE Vb. Photomicrograph, (x115) with plane polarized light, of the glassy rhyolite of the surface phase of Little Glass Mountain flow. The glass of the ground mass carries scattered plagioclase tablets. The globules, drawn out and contorted by the flow movement, are holocrystalline and contain none of the tablets.

tively flat, rising with a very low gradient toward the centers of extrusion. Hoffmann Flow rises about 200 feet in three miles, a gradient of about one and a half per cent, and Medicine Flow has a slightly greater average slope. In detail, however, the surfaces are extremely rugged with a relief of as much as 50 feet. There has been no formation of residual soil on the tops of the flows, but depressions in the surface have been partly filled by drifted pumice from later eruptions. In these pumice-filled pockets and in fractures in the lava, the scrubby pines and some minor vegetation have gained a foothold. Most of the surface, however, is barren, unaltered lava.

Both flows are composed of a dense, dull lustered rock in which a few small plagioclase phenocrysts are visible in an aphanitic groundmass. Some of the surface lava shows textural variations ranging from coarse scoria to finely vesicular pumice, but the relative amount of the vesicular phase is small.

The typical dense variety contains from 7 to 10 per cent of phenocrysts in a microcrystalline groundmass. Most of the phenocrysts are zoned crystals of andesine with an average composition of An_{40} . The individuals are bounded by well-developed crystal-faces, have an average length of about one millimeter, and are twinned after the albite, Carlsbad and pericline laws. The other phenocrysts are well-formed prisms of pyroxene, mostly hypersthene containing iron and magnesia in the molecular ratio of $FeSiO_3:MgSiO_3::25:75$, but a few are monoclinic with the optical constants of common augite. A fraction of a per cent of iron ore is disseminated through the rock, occurring both as rod-shaped grains and octahedral or globular masses. The groundmass is made up of about 50 per cent of minute tablets of twinned plagioclase in more or less trachytic arrangement, with indeterminable crypto-crystalline material filling the interstices.

The petrography of the vesicular types differs in one respect, aside from the vesicularity, from that of the dense phase. Through the groundmass of the vesicular rocks are scattered numerous minute areas (as much as 10 per cent in some specimens) which are slightly darker in color than the bulk of the groundmass, and which are free from the feldspar microlites which characterize the rest of the rock (see Plate Va). These patches are somewhat irregular in shape but in general are equant and nearly circular,

with well-defined boundaries against the groundmass. The material of the globules is perceptibly crystalline, but individual crystals can not be distinguished. They do not show the radiating-fibrous structure typical of small spherulites. The history of crystallization of these globules undoubtedly has been different from that of the bulk of the groundmass which is characterized by feldspar tablets, though no entirely satisfactory explanatory theory has yet presented itself.

Chemical analyses were made of a specimen of the dense, common phase, and two specimens of the vesicular types which contain the strange globules; Table I, columns 19000, 19018, and 19018a respectively. There is very little difference between the three analyses. One vesicular rock contains more ferric oxide than do the other two, and both vesicular rocks are slightly richer in the alkali feldspars than the dense phase. The increase in alkali feldspar may be due to the presence of the globules. All three are similar to the dacites of Lassen Peak. The Lassen dacites, however, all contain biotite, while no traces of biotite have been found in the Medicine Lake rocks.

Rhyolite. Little Glass Mountain is typical of the rhyolitic lava eruptions of Recent age. The flows cover an elliptical area about three miles long and two miles wide on the outer slope of the southwest rim of the Medicine Lake basin. The highest point of the pile is near the northwest edge of the area covered by the lava, probably over the vent from which the flows were extruded. The total thickness of the lava pile at this point must be between 800 and 1,000 feet. On the margins, the flows are from 100 to 150 feet in thickness. The flow fronts are similar in appearance to those of Medicine and Hoffmann Flows. The flow surface rises from the margins toward the center by a series of alternating steep and gradual elevations giving a terraced effect in profile. In detail, the character of the surface of each terrace is somewhat comparable with that of the dacite flows, though a great deal more pumiceous slag is found on the surface of the rhyolite.

The flows are made up of a great many textural varieties of a porphyritic obsidian. Most of the surface rock is an exceedingly porous, glass sponge. The porespace is much larger than those of a typical pumice, but the ratio of porespace to glass is sufficient to allow the rock to float on water. Another extreme textural phase is a glassy scoria with cavities as large as a man's fist which are

usually partly lined with thin scales and rosettes of microcrystalline rhyolite. All gradations in vesicularity between dense obsidian and these two extreme phases may be found interbanded with each other in rather well-defined layers. The bands, varying from a few inches to tens of feet in thickness, are, in some cases, highly contorted and, in all cases, show some evidence of flow movement after the banding had been produced. Where the flow fronts have been somewhat broken down the dense obsidian is the dominant type, and it is quite probable that a crystalline phase exists at greater depth in the flows.

The rock is a glass with a few crystals of plagioclase and hypersthene as phenocrysts, identical with those which are found in the earlier dacite. The number of phenocrysts varies in different specimens but some are present in every textural phase of the rock, and no concentration by settling in the flow can be detected. The groundmass is rhyolitic glass carrying 10 or 15 per cent of plagioclase crystallites which are usually oriented with their long axes in the planes of flowage. A specimen of the dense obsidian, No. 19033a, analysed by E. S. Shepherd, has the composition of a rhyolite with 73.3 per cent of SiO_2 . The index of refraction of the glass for sodium light is $1.491 \pm .0005$, and its specific gravity is $2.39 \pm .01$.

In the vesicular phases, increasing in number with the increase in vesicularity, are found elongated areas of apparently holocrystalline material so finely crystalline that the individuals are not determinable (see Plate Vb.) The texture and crystallinity of these areas is the same as that of the similar areas found in the vesicular dacite. The boundary is sharp between these blebs and the glass of the groundmass. The shape of cross-sections of these bodies varies from nearly circular to extremely thin and contorted lens-shapes. In all cases, the shape appears to be dependent on the flow structure of the rock. The general form and relation to flow lines suggests that these crystalline bodies represent globules of material, isolated from the bulk of the lava, which have been drawn out and contorted by the movements of the flow prior to complete consolidation. An occasional lens may be traced through a narrow thread of crystalline material into an open vesicle which has a thin cryptocrystalline lining. Apparently the origin of the elongated crystalline lenses, of the vesicles, and of the crystalline vesicle-lining has some common control. A number of samples of the

vesicular glass, containing as much as 20 per cent of the crystalline blebs, were analysed by E. S. Shepherd and were found to have a remarkably uniform composition which is identical with that of the dense obsidian.

The index of refraction of the glass from the specimens containing the crystalline bodies is the same to the third decimal place as that of the dense obsidian. The two glasses, therefore, must have the same chemical composition and, further, the crystalline blebs must have a similar composition since their presence or absence does not change the bulk composition of the rock.

Big Glass Mountain Complex. Big Glass Mountain, whose flows cover an area of about nine square miles, is the largest accumulation of Recent siliceous lava in the region. The high point of the mountain has an elevation of 7850 feet, and the probable elevation of the pre-flow surface beneath the peak is 7050 feet, giving a possible thickness of 800 feet at the center of the pile. The vent, marked by this peak, was located on the eastern rim of the Medicine Lake basin, so that the lava flowed both down the inner slope toward the basin floor and down the outer slope of the Medicine Lake Highland. The most extensive flows reached a distance of about five miles from the vent, covering the outer slope down to an elevation of about 5,000 feet,

The slopes of the mountain are formed by a series of terraces or steps, of which there are three on the western side and seven on the long eastern side. Each of these terraces seems to be formed by an individual gush or wave of lava which has solidified with a precipitous wave-front from 100 to 200 feet high. (See Plate VI.) The three top waves are fairly symmetrical about the center of eruption, so that the top of the mountain resembles a pile of three discs, progressively smaller in area, one on top of the other.

The lavas of the Big Glass Mountain flows range in composition from rhyolite to dacite. The southeastern tongue which extends the farthest from the vent is similar in structure and appearance to the dacitic Hoffmann Flow, except for its lack of vegetation. The greater part of the rock is a holocrystalline dacite porphyry which is similar in texture and mineral composition to the earlier dacite of both Hoffmann and Medicine Flow. Its chemical composition, given in Table I, column 19106, is practically identical with that of the Medicine Flow rock. In one respect the late dacite flow differs radically from the older two dacite bodies. A large streak of



PLATE VI. Aerial view of the source of the Big Glass Mountain flows. The last gush stands out sharply. The general contour of the surface gives striking evidence of the extreme viscosity of the flow. The contrasting color of different surface wrinkles is due to different vesicularity of the surface froth. The different flow fronts are from 100 to 200 feet high. Photo, Brubaker Aerial Surveys, Portland, Oregon.

glassy obsidian, about 30 feet wide and 100 feet long, is exposed in the surface of the dacite flow. Field relations force the conclusion that it was an integral part of the dacite flow, but there is no sign of gradation between the two rock bodies. The obsidian is strikingly different from the dacite, being a nonporphyritic glass with only a small percentage of feldspar microlites. Herdsman and Shepherd analysed the rock with the results which are given in Table I, columns 19103. The differences between the two analyses are probably no greater than those resulting from slightly different analytical technique. The rock is a rhyolite similar to that of Little Glass Mountain. The index of refraction of the glass is $1.4930 \pm .0005$ and its specific gravity is $2.38 \pm .01$.

The next higher terrace of the eastern slope appeared from a distance to be a flow of rhyolitic obsidian and slag overlying the dacite flow.

The fourth terrace from the top is made up of a complex of interbanded obsidian and vesicular slag. The rock has a dull luster and shows a larger number of feldspar microlites than the obsidian from the lens in the dacite. The index of refraction is $1.497 \pm .001$ and the specific gravity is $2.45 \pm .01$. A chemical analysis by Shepherd (Table I, column 19103c) shows that the rock has a composition between the rhyolite and the dacite. Across the top of this terrace is a lens of glassy obsidian about 50 ft. wide and several hundred feet long. The rock is similar to the other rhyolitic obsidians in appearance and index of refraction and undoubtedly has the same composition. To all appearances it was an integral part of the flow with the intermediate composition.

The third terrace from the top, overlying the lava just described, is a flow of rhyolitic glass and froth interbanded on a gigantic scale. Some of the vesicular streaks are 50 feet in width. The dense obsidian has the composition given in Table I, column 19103b. Its index for sodium light is $1.4915 \pm .0005$ and its specific gravity is $2.39 \pm .01$. The rock has no phenocrysts and only a few feldspar microlites. A specimen of the associated pumiceous rock was found by Shepherd to have almost exactly the same composition.

Pumice. Outbursts of pumice preceded the eruption of the Recent rhyolitic lava. The most violent of these eruptions occurred just west of the Little Glass Mountain vent. A large cone was built at this point, Pumice Stone Mountain, which has an elevation of 7,300 feet, about 800 feet above the prepumice surface. Just south

of the big cone is a smaller one which is perfectly preserved. The throat of this cone is lined with red pumice whose color is due to disseminated scales of hematite, formed by the action of the gases escaping from the vent.

Two small pumice vents were opened in the locality northwest of Medicine Lake. They both have blown open older basaltic cinder cones, so the piles surrounding the vents are mixtures of basaltic cinders and rhyolitic pumic.

Several small cones are found at the northern edge of Big Glass Mountain. The existing cones are so close to the edge of the lava that it may well be presumed that part of the pumice record has been obliterated by the lava flows.

An analysis of the rhyolitic pumice from Pumice Stone Mountain is given in column 19041, Table I. The rock has typical pumice texture and is composed of glass with a few phenocrysts of plagioclase and hypersthene. A bit of glass from a streak in a bread-crust bomb has an index of refraction of $1.4915 \pm .0005$.

PETROLOGY

INTRODUCTION

The lavas of the Modoc Lava-bed Quadrangle range in composition from olivine-rich basalts to rhyolites. Their field affinity with the main Cascade volcanoes in northern California indicates that they belong in the Cascade volcanic series. The mineralogy and chemistry of the Modoc rocks conclusively relates them to the Cascade lavas. This series of Cascade rocks, typified by the lavas from Lassen Peak, has been discussed by Bowen as a normal sub-alkaline series derived by fractional crystallization in the hornblendic line of descent from primary basaltic magma. Bowen's line of attack has been employed in this study of the petrology of the Modoc lavas. In the detailed consideration of the relations of the different lavas, a number of points were encountered which are at variance with Bowen's thesis. These observations are summarized in the following pages, but no attempt is made to fit them into existing petrologic theory.

BASALTS

Lavas of basaltic composition were erupted during every period of volcanic activity in the Modoc area, and have a greater areal distribution than any other type. However, they show only slight variation in their chemical composition. The average of six analyses

of these basalts is comparable to the composition of the average Mull basalt of the Porphyritic Central Type²¹ and differs notably in alumina and iron oxide from the average of 63 plateau basalts described by Washington.²²

Bowen gives convincing evidence that the anorthite-rich rocks of the Mull Porphyritic Central Type have been derived by the concentration of early-formed crystals.²³ Accepting Bowen's conclusion, the composition of the basalts of the Modoc and their intimate field association with andesitic volcanoes indicate that they have been derived by the concentration of calcic plagioclase and magnesian olivine during the differentiation of the andesitic magma. The Modoc rocks differ from the Mull porphyries in that they contain no relic phenocrysts of plagioclase.

	PLATEAU BASALTS	BASALTS FROM MODOC	MULL PORPHYRITIC CENTRAL TYPE
SiO ₂	49.5	49.4	50.0
Al ₂ O ₃	13.6	18.3	18.0
Iron oxide	13.0	8.7	9.0
MgO	6.3	8.2	5.0
CaO	9.3	10.4	10.0
Na ₂ O	2.7	2.7	2.5
K ₂ O	0.9	0.5	0.4
TiO ₂	2.3	0.9	1.3

Of the analysed Modoc specimens, the basalts which show the greatest chemical similarity are three which were erupted from different centers in three different periods of volcanism: No. 19141 from the Cedarville andesite; No. 19071 from the Massive Lava Group; and No. 19123 from the Warner Basalt. These rocks contain 62 per cent of calcic labradorite (an 68), 23 per cent of forsterite-rich olivine, 12 to 15 per cent of pyroxene, and a small amount of magnetite. K₂O is less than 0.3 per cent in all of them. They seem to represent an extreme concentration of anorthite and forsterite, yet they carry no relic phenocrysts.

Two analysed specimens (Nos. 19142 and 19143) from the Modoc Basalt show a greater chemical variation. The less siliceous one (and the older in the chronological column) contains 65 per cent of medium labradorite (an 58 norm minerals), 10 per cent of

²¹ Thomas, H. H., and Bailey, E. B. Tertiary and post-Tertiary Geology of Mull, p. 22, 1924.

²² Washington, H. S., Deccan traps and certain other plateau basalts; *Bull. Geol. Soc. of Am.*, **33**, p. 797, 1922.

²³ Bowen, N. L., The Evolution of Igneous Rocks, Princeton, Chap. 9, 1929.

olivine, and has 0.5 per cent of K_2O . The more siliceous one (and younger) contains 65 per cent of calcic andesine (an 47), 5 per cent of norm quartz, and has 1.6 per cent of K_2O . The change from olivine to quartz in the norm, and the increase of the alkali feldspars at the expense of anorthite are the most striking differences between the two. The geologic relations of the basalts of this group indicate that all of them were erupted from the same general center and presumably are differentiates from the same local magma. The pair of analyses then should be excellent material for a quantitative study of differentiation. A simple calculation shows the difference between the two analyses in term of norm minerals. To produce the more siliceous rock, 55 per cent of plagioclase (an 60) and 25 per cent of olivine containing about 50 per cent by weight of fayalite must be subtracted from the less siliceous one. Theoretically, the first 55 per cent of plagioclase crystals from a melt of the composition of the less siliceous rock would have, if reaction kept pace with crystallization a composition of ab 38—an 62. This is almost exactly the composition computed for the plagioclase representing the difference between the two rocks. The computed olivine is richer in fayalite than is the melt from which it must precipitate, whereas the actual crystals which would form would contain only about 20 per cent of fayalite. Removal of the early natural olivine would leave a residual liquid containing a greater amount of iron silicate than is contained in the rock which we wish to produce.²⁴ There is no natural phenocryst-forming mineral in which the concentration of iron with respect to magnesia is so great that its removal instead of olivine would give the desired Fe/Mg ratio in the melt. A possible combination might be the removal of the necessary amount of magnesia-rich olivine by fractional crystallization, and the removal of the excess iron and silica from the residual liquid by other means. It is not reasonable to assume removal of quartz phenocrysts from basaltic magma. Nor is it likely, judging from the textural evidence offered by basaltic rocks, that magnetite forms early as phenocrysts in any appreciable quantity. There is considerable evidence according to Fenner and Zies that magnetite is carried in notable quantities by volatiles.

²⁴ The concentration of iron in the residual liquid during crystallization of basaltic magma is one of the strong objections advanced by Fenner against the thesis that fractional crystallization is the only important factor in the differentiation of magmas.

Surely there would be a very marked concentration of volatiles in the residual liquid in the case being considered where 80 per cent of the original magma must be crystallized before the residual liquid reaches the desired composition. If the excess iron and silica be disposed of by removal with escaping volatiles, a residual liquid with the composition of the siliceous basalt may be derived from the less siliceous rock.

The holocrystalline basalts of the area may be separated into two groups on the basis of texture: the one, ophitic group, in which the pyroxene and plagioclase have the poikilitic relation known as ophitic and sub-ophitic texture; the other the intergranular group, in which pyroxene and plagioclase each occur in hypidiomorphic crystals which bear an intergranular relation to each other. The dividing line between the two groups is very sharp though, of course, those rocks which are partly glassy can not always be assigned with assurance to one or the other group. Neither augite nor hypersthene is present as phenocrysts in either type of basalt.

The writer has never seen the description of an ophitic basalt which contains pyroxene phenocrysts, whereas their occurrence in many intergranular basalts and low-silica andesites is commonly known. Further, as Washington mentioned²⁵ but did not stress, the composition of phenocrysts pyroxene is entirely different from that of the pyroxene of an ophitic basalt.²⁶ The relative molecular proportions of CaO, MgO, FeO, and Fe₂O₃ in the average analysis of eight augite phenocrysts²⁷ and three ophitic pyroxenes²⁸ is given for comparison. The ratio of iron to magnesia, low in the phenocrysts and high in the ophitic pyroxene, points to an early crystallization of the former and a late crystallization of the later.

	CaO	MgO	FeO	Fe ₂ O ₃
Phenocryst pyroxene	47.0	43.0	8.0	2.0
Ophitic pyroxene	34.0	38.0	27.—	0.5

Thus it would appear that the ophitic texture represents a set of conditions under which pyroxene can not crystallize as pheno-

²⁵ Washington, H. S., *loc. cit.*, p. 798.

²⁶ Since the preparation of this manuscript, Barth has studied the difference in composition between phenocryst and groundmass pyroxene and showed that they probably represent a continuous reaction series between wo, en, and hy. Barth, Tom Crystallization of pyroxenes from basalts; *Am. Min.*, **16**, pp. 195-208, 1931.

²⁷ Augites from Haleakala, Vesuvius, Etna, Kilimanjaro, Alban Hills, Stromboli, and Nishigatake analysed by Washington and others.

²⁸ Pyroxenes from the Goose Creek diabase and Whin sill and related dikes.

crysts, and the intergranular texture, a set of different conditions under which pyroxene is able to crystallize as one of the early minerals and form phenocrysts.

Many of the basalts show variable amounts of glass which always contains most of the iron oxide in dendritic crystals. In some rocks with a large amount of glass no crystalline pyroxene is present. One such rock was analysed, No. 19116, and a comparison of the norm, mode, and calculated norm of the glass gives an insight into the progress of crystallization in that lava.

		NORM		MODE		NORM OF GLASS
or	4.4					6.
ab	28.3	spar	63.9	labradorite	41	25.
an	31.2					22.
wo	5.5					13.
en	11.1	px	28.6	glass	44	6.
hy	12.0			(with iron oxide)		8.
ol	2.2			olivine	15	—
qu						11.
mt	2.1					5.
il	2.4					

The Lake basalt contains 73 per cent of feldspar which has a composition (from the norm) of or 5—ab 35—an 60.²⁹ In a feldspar melt of this composition, less than five per cent can exist as crystals with a composition ab 15—an 85. In the rock, the unzoned cores of the phenocrysts have this composition but make up about eight-tenths of the bulk of the phenocrysts or about 33 per cent of the total feldspar. It is obvious that these phenocrysts could not have formed in equilibrium with a melt of the composition of the rock. The nature of several definite stages in the development of the phenocrysts is clearly indicated by a study of the textural relations and composition of the rock constituents. However, the nature of the processes which brought about these stages is a matter of speculation.

The slightly zoned cores of the plagioclase phenocrysts which make up eight-tenths of their volume or twenty-four per cent of the rock indicate that equilibrium was maintained between melt and phenocrysts during most of the time involved in their growth. At the end of this time the phenocrysts had a composition of An 85 and a melt in equilibrium with such a plagioclase would contain

²⁹ These calculations were made on the material analysed by Herdsman which contained 30 per cent of phenocrysts.

plagioclase with An 60. The zoned margin of the phenocrysts shows that the next step was a period of crystallization under conditions which did not permit equilibrium and with a rapid change in environment. Further, the zoned margin is divided into two stages, the later of which coincides with the crystallization of the groundmass after extrusion. The groundmass contains plagioclase with only 45 parts of anorthite. Therefore, during the short time represented by the inner band of zoning, the environment of the phenocrysts was changed from a melt containing plagioclase An 60 to one with plagioclase An 45.

There are two general ways in which this could be accomplished: either by transferring the phenocrysts from one liquid to another or by changing the composition of the liquid without moving or altering the phenocrysts. Transferring the phenocrysts would involve either floating or sinking the early crystals into another part of the magma. Changing the liquid could be done either by mixing with another magma of appropriate composition, by concentrating a liquid fraction of appropriate composition which was immiscible in the parent magma, or by selective transfer of certain elements from one part of the magma to another.

There are two important objections to the processes involving gravitative movement of phenocrysts. First, in any given case, the question of whether or not the crystals will float, sink, or remain suspended is a matter of conjecture. It certainly does not depend entirely on the relative specific gravity of the crystals to the liquid rock as we can estimate them in the laboratory. Factors such as viscosity and rigidity of the liquid under small forces must be equally important, and can not be estimated quantitatively. Second, the maintenance of appropriate temperature relations between different zones of magma in a system which would produce such a rock as the Lake basalt is almost too complicated in its adjustment to be reasonable.

Mixing of two magmas with different compositions seems possible. Evidence from the rock requires only that the mixing must have been perfect, as there are no streaks or bodies of variable composition.

The two other possible methods involve a change of composition of the liquid by differential movement of constituents, either by liquid immiscibility or by transfer with volatiles. Fenner³⁰ and

³⁰ Fenner, C. N., The Katmai magmatic province; *Jour. Geol.*, **34**, pp. 673-772, 1926.

Bowen³¹ have recently discussed the role of volatile constituents in magmas, but still the knowledge concerning their amount and behavior in a magma is far from complete. The question of limited miscibility in dry silicate melts has been settled conclusively in laboratory experiments.³² However, limited miscibility in systems involving water and other volatile constituents has not been disproved, and until such proof is forthcoming, one may be justified in considering limited miscibility as a possible phenomenon.

DACITE AND RHYOLITE

The location of the Recent flows of dacitic and rhyolitic lava on the top of the Medicine Lake Highland indicates that they represent small bodies of magma developed within the Highland volcanic focus.

The two dacite flows, Medicine Flow and Hoffmann Flow, are next younger in age than the platy andesite flows from the same focus. The difference in composition between the Medicine Flow dacite and the platy andesite may be represented by 35 per cent of plagioclase An 25, 4 per cent of augite, 5 per cent of magnetite, $1\frac{1}{2}$ per cent of ilmenite, and $1\frac{1}{2}$ per cent of quartz (all norm minerals). This general assemblage of minerals is not greatly different from those which one would expect to find as early phenocrysts in the platy andesite magma, except that the plagioclase has an impossible composition. The calculated phenocrysts have the same composition as the total plagioclase of the magma. The natural early crystals would be decidedly more calcic than the magma, so this fact alone rules out the possibility of expressing the difference between the two rocks solely in terms of early phenocrysts. The composition of one or both magmas has been influenced by some factor other than the removal of early phenocrysts.

The chemical composition of all the rhyolite which is present as pure glass is remarkably constant. Four analyses of obsidians from both Big and Little Glass Mountains are almost identical. They also are quite similar to the older obsidian of the Massive Lava Group. If these compositions be expressed in terms of normative quartz and feldspar, their mutual resemblance becomes even more striking, and their approach to the composition of Vogt's graphic granite anchi-eutectic is most impressive.

³¹ Bowen, N. L., *The Evolution of Igneous Rocks*, Chap. 14, 1928.

³² Greig, J. W., Immiscibility in silicate melts; *Am. Jour. Sci.*, **13**, pp. 1-44, 133-154, 1927.

Bowen, N. L. *The Evolution of Igneous Rocks*, Chap. 2, 1928.

Anchi-eutectic	qu:or:plag::26:29:45	or:plag::40:60
Obsid. Massive Lava Gr.	qu:or:plag::32:28:40	or:plag::41:59
Obsid. Little Glass	qu:or:plag::31:27:42	or:plag::39:61
Obsid. Big Glass	qu:or:plag::30:27:43	or:plag::38:62
Obsid. Big Glass	qu:or:plag::30:28:42	or:plag::40:60
Obsid. Big Glass	qu:or:plag::31:28:41	or:plag::41:59

The difference between the dacite and the typical rhyolite may be calculated in terms of norm minerals. It amounts to 27 per cent of plagioclase (An 52), 8 per cent of hypersthene (FeSiO_3 51 MgSiO_3 49). The computed plagioclase has a composition which agrees with that of the first 27 per cent of crystals which would form from the dacite magma, but the computed hypersthene is much richer in iron than the natural hypersthene which exists in the dacite as phenocrysts. Here, as in the case of the Modoc basalts, excess iron would have to be removed from the residual liquid to give the composition of the rhyolite.

The two older dacitic flows are made up of uniform dacite throughout. Likewise, Little Glass Mountain and two small flows consist of rhyolitic glass and pumice of remarkably uniform composition. However, Big Glass Mountain ranges in composition from the type dacite to the type rhyolite. It presents a problem in differentiation which was not solved satisfactorily in the course of this work. However, the texture of both the dacite and rhyolite shows phenomena which may have a decided significance in an interpretation of their differentiation.

The vesiculated rhyolite from all of the glassy flows contains minute globular or lenticular bodies of cryptocrystalline material which have sharp boundaries against the glass of the groundmass. Deformation of these bodies was caused by the flow-movement of the rock so they must have existed before movement ceased. They are often linked with open vesicles lined with a thin shell of cryptocrystalline material which formed due to volatiles within the vesicles. The material in the globular bodies must have the same composition (at least with regard to the major constituents) as the typical rhyolite, as a specimen which contains over twenty per cent of the globules had a chemical composition identical with another in which no trace of the globular material could be found.

The surface specimens from the dacite flows show similar small bodies. There they are more minutely crystalline than the groundmass and stand out because of their finer texture and the absence in them of the plagioclase tablets of the main groundmass. Three samples from a dacite flow were analysed: the type dacite, No.

19099; an unoxidized vesicular phase, No. 19018; and a vesicular phase showing deutric oxidation of iron No. 19018a. Both vesicular specimens showed the small globular bodies, and all three showed the same percentage of phenocrysts as determined by the Rosiwal method. Ferric iron is high in the specimen which showed the oxidation. Otherwise the three analyses differ only slightly. The two surface phases, however, show a similar departure from the dense phase, namely a slight increase in potash feldspar and free silica. This difference conceivably may be caused by the presence of the small globular bodies which probably have a composition similar to those in the rhyolite.

The exact nature of the origin of these globular bodies is not obvious. That they are of primary origin seems clearly indicated by their textural relations. The fact that they occur only in vesiculated surface rock, and are often connected with open viscicles seem to relate them to the presence of volatile constituents. For want of a better explanation, it is suggested here that these bodies represent a liquid fraction, rich in volatiles and with a silicate composition similar to that of Vogt's graphic-granite anchieutectic, which separated from the relatively dry magma due to limited miscibility.³³ If this be true, it is possible that the small bodies of rhyolite were formed by the separation of this material from larger bodies of dacite within the volcanic focus.

TABLE 1

	19141	19123	19071	19142	19116
	Gonyer	Herdsmen	Gonyer	Gonyer	Herdsmen
SiO ₂	46.00	47.10	47.26	48.98	51.46
Al ₂ O ₃	18.24	18.52	18.56	18.92	17.69
TiO ₂	0.74	0.90	0.88	1.16	1.25
Fe ₂ O ₃	2.00	tr	1.42	2.22	1.37
FeO	7.43	7.91	7.96	7.12	9.05
MnO	0.12	tr	0.08	0.09	0.18
MgO	10.04	10.89	9.62	7.42	5.13
CaO	11.56	11.98	11.54	10.04	8.92
Na ₂ O	2.34	2.33	2.24	3.04	3.37
K ₂ O	0.22	tr	0.20	0.44	0.77
H ₂ O+	1.51	0.10	0.30	0.34	0.44
H ₂ O-	0.18	0.18	0.06	0.05	0.30
P ₂ O ₅	0.04	0.09	0.08	0.14	0.14
	100.42	100.00	100.20	99.96	100.07

³³ Such an immiscible fraction is considered possible by Arrhenius and Evans. Arrhenius, S., *Worlds in the Making*, Harper, p. 20, 1908. Evans, J. W., *Quart. Jour. Geol. Soc.*, **81**, pt. 2, p. 341, 1925. Evans, J. W., *Faraday Soc.*, Symposium on Physical Chem. etc. p. 465, 1924. Evans, J. W., *Cong. Geol. Internat. (Canada)*, p. 248, 1913.

TABLE I (Continued)

qu	—	—	—	—	—
or	1.1	—	1.1	2.2	4.5
ab	17.3	17.8	18.7	25.2	28.3
an	38.6	40.0	41.7	37.0	31.2
ne	1.1	0.8	—	—	—
di	15.2	15.1	12.0	9.7	10.2
hy	—	—	3.3	10.0	18.4
ol	20.6	23.9	19.6	9.6	2.2
mt	3.0	—	2.1	3.3	2.1
il	1.4	1.7	1.6	2.3	2.4
ap	0.2	0.3	0.3	0.4	0.4
wo ¹	7.9	7.8	6.1	5.0	5.5
en	5.1	4.9	6.1	10.2	11.1
hy	2.2	2.4	3.0	4.5	12.0
	19144	19144	19086	19143	19145
	Gonyer	Herdsmen	Gonyer	Gonyer	Gonyer
SiO ₂	49.66	49.80	54.56	55.46	57.22
Al ₂ O ₃	19.79	21.81	17.52	17.70	19.16
TiO ₂	1.12	1.04	1.28	0.68	0.92
Fe ₂ O ₃	4.80	1.64	8.70	1.58	2.21
FeO	5.40	6.43	0.32	5.12	4.55
MnO	0.06	tr	0.04	0.08	0.12
MgO	4.16	4.40	4.34	5.86	3.32
CaO	10.90	10.82	8.14	8.12	6.12
Na ₂ O	3.37	3.04	3.94	3.00	4.28
K ₂ O	0.72	0.60	0.90	1.58	1.64
H ₂ O+	0.18	0.10	0.10	0.50	0.81
H ₂ O—	—	0.10	0.05	0.01	0.05
P ₂ O ₅	.17	0.10	0.22	none	0.11
	100.33	99.88	100.11	99.69	100.51
qu	—	—	7.0	4.8	6.4
or	3.9	3.3	5.6	9.4	9.4
ab	28.8	25.7	33.5	25.2	36.2
an	36.7	44.2	27.2	30.3	28.4
di	13.4	7.0	6.9	8.1	0.9
hy	7.3	10.6	7.6	17.8	13.0
ol	0.6	4.1	—	—	—
mt	7.0	2.3	lm 8.6	2.3	3.3
il	2.1	2.0	0.6	1.4	1.7
ap	0.3	0.3	0.3	—	0.3
			tn 2.4		
wo	7.0	3.6	3.7	4.2	0.5
en	9.8	8.0	10.8	14.7	8.1
hy	4.0	6.0	—	7.0	5.3

¹ Proposed Change in Calculation of Norms of Rocks, T. F. W. Barth, *Min. und Pet. Mit.*, **42**, 1931, pp. 1-7.

TABLE I (Continued)

	19063	19064	19106	19099	19018
	Gonyer	Gonyer	Herdsmen	Herdsmen	Gonyer
SiO ₂	59.98	59.98	67.20	67.70	68.12
Al ₂ O ₃	16.71	17.28	16.22	16.32	15.73
TiO ₂	1.30	1.20	0.30	0.30	0.42
Fe ₂ O ₃	2.52	2.56	0.34	0.27	0.32
FeO	5.04	4.88	3.03	3.20	2.74
MnO	0.11	0.15	tr	tr	0.03
MgO	2.22	2.10	1.32	1.25	1.24
CaO	4.84	4.72	3.43	3.35	3.30
Na ₂ O	5.12	4.92	4.02	3.89	3.56
K ₂ O	1.63	1.68	3.36	3.22	3.78
H ₂ O+	0.19	0.21	0.32	0.22	0.31
H ₂ O—	nd	nd	0.12	0.05	nd
P ₂ O ₅	0.43	0.44	0.06	0.06	0.12
S	nd	nd	0.20	0.20	nd
	<hr/> 100.09	<hr/> 100.12	<hr/> 99.92	<hr/> 100.03	<hr/> 99.67
qu	9.9	10.7	19.7	21.8	22.4
or	9.6	9.9	20.0	18.9	22.2
ab	43.1	41.5	34.1	33.0	29.9
an	17.9	20.1	16.1	15.9	15.6
C	—	—	—	0.6	0.1
di	2.8	0.4	—	—	—
hy	9.3	10.1	8.1	8.1	8.0
mt	3.7	3.7	0.5	0.5	0.5
il	0.9	0.9	0.6	0.6	0.8
ap	1.0	1.0	0.3	0.3	0.3
wo	1.4	0.2	0.0	0.0	0.0
en	5.6	5.3	3.3	3.1	3.1
hy	5.1	4.9	4.8	5.0	4.9
	<hr/> 19018a	<hr/> 19041	<hr/> 19044	<hr/> 19103c	<hr/> 19103b
	Shepherd	Herdsmen	Herdsmen	Shepherd	Shepherd
SiO ₂	68.44	71.30	71.50	72.64	73.34
Al ₂ O ₃	15.44	13.76	14.66	14.07	13.35
TiO ₂	0.49	0.20	0.22	0.36	0.30
Fe ₂ O ₃	1.17	0.47	0.33	0.77	0.58
FeO	2.08	2.02	2.28	1.45	1.27
MnO	0.04	tr	tr	0.02	0.02
MgO	1.46	0.42	0.44	0.49	0.37
CaO	3.47	1.66	1.50	1.60	1.41
Na ₂ O	3.72	3.85	4.53	4.25	4.13
K ₂ O	3.32	3.88	4.07	4.08	4.45
H ₂ O+	0.31	1.95	0.20	0.11	0.33
H ₂ O—	0.08	0.35	tr	nd	0.03
P ₂ O ₅	0.21	0.03	none	0.11	0.18
Cl	0.03	nd	nd	nd	0.08
S	0.03	0.21	0.21	nd	0.10
BaO	0.06				
	<hr/> 100.35	<hr/> 100.10	<hr/> 99.94	<hr/> 99.95	<hr/> 99.94

TABLE 1 (Continued)

qu	24.5	28.8	24.0	27.8	28.9
or	19.5	22.8	24.5	24.5	26.7
ab	31.4	32.5	38.2	35.6	34.6
an	15.6	8.0	7.2	7.2	4.5
C	—	0.2	—	—	—
di	0.9	—	—	—	1.4
hy	5.1	3.9	4.7	2.7	1.5
mt	1.9	0.7	0.7	1.2	0.9
il	0.9	0.5	0.5	0.8	0.6
ap	0.3	0.1	—	0.3	0.3
wo	0.5	0.0	0.0	0.0	0.7
en	3.5	1.0	1.1	1.2	0.9
hy	2.0	2.9	3.6	1.5	1.3

	19103 Herdsman	19103 Shepherd	19033a Shepherd	19007 Herdsman
SiO ₂	72.75	73.59	73.59	74.10
Al ₂ O ₃	14.34	13.78	14.03	13.33
TiO ₂	0.20	0.27	0.31	0.20
Fe ₂ O ₃	tr	0.60	0.42	tr
FeO	2.10	1.30	1.43	1.68
MnO	tr	0.02	0.02	tr
MgO	0.43	0.33	0.36	0.38
CaO	1.34	1.39	1.38	1.45
Na ₂ O	3.73	4.19	4.04	3.86
K ₂ O	4.27	4.32	4.34	4.50
H ₂ O+	0.30	0.14	0.12	0.29
H ₂ O—	0.22	nd	0.06	0.05
P ₂ O ₅	nil	0.12	0.09	nil
Cl	nd	nd	0.03	nd
S	0.22	nd	0.02	0.22
	99.90	100.05	100.24	100.06

qu	29.4	28.8	29.7	30.0
or	25.6	25.6	25.6	26.7
ab	32.0	35.6	34.1	32.5
an	6.4	6.1	6.1	5.6
C	1.0	0.2	0.4	—
di	—	—	—	1.4
hy	4.3	2.1	2.5	2.8
mt	0.2	0.9	0.7	0.2
il	0.5	0.6	0.6	0.5
ap	—	0.3	0.3	—
wo	0.0	0.0	0.0	0.7
en	1.0	0.8	0.9	0.9
hy	3.3	1.3	1.6	2.6

- 19141 Basalt, ophitic. Cedarville andesite, Stone Coal Valley near Pit River bridge. "III, 5, 4, 5.
- 19123 Basalt, ophitic. Warner Group, Laird's Ranch. "III, 5, 4, 5.
- 19071 Basalt, ophitic. Massive Lava Group, Bear Mountain. (II)III, 5, 4, 5.
- 19142 Basalt, ophitic. Modoc Basalt, near Burnt Lava Flow. II(III), 5, 4, "5.
- 19144 Basalt, porphyritic. Massive Lava Group, near Medicine Lake. Gonyer analysis, II, 5, "4, (4)5. Herdsman analysis, II, 5, 4, (4)5.
- 19116 Basalt, intersertal. Modoc Basalt Group, near Sharp Mountain. II(III), 5, (3)4, (4)5.
- 19086 Basalt, intergranular. Modoc Basalt Group, cinder cone northwest of Medicine Lake. II, (4)5, 3'', 4(5).
- 19143 Basalt, intergranular. Modoc Basalt Group, Burnt Lava Flow. II, "5, (2)3, 4.
- 19145 Andesite, porphyritic. Massive Lava Group, Garner Mountain. II, "5, 3, 4.
- 19063 Andesite, trachytic. Platy Andesite Group, south of Medicine Lake, platy phase. II, 4(5), (2)3, 4''.
- 19064 Andesite, trachytic. Surface phase of 19063. "II, 4(5), "3, 4''.
- 19106 Dacite, porphyritic. Obsidian Group, Big Glass Mountain. I(II), 4, 2(3), (3)4.
- 19099 Dacite, porphyritic. Obsidian Group, Medicine Flow. I(II), 4, 2(3), (3)4.
- 19018 Dacite, porphyritic. Obsidian Group, surface phase of Medicine Flow. I(II), 4, (2)3, 3''.
- 19018a Dacite, porphyritic. Obsidian Group, oxidized surface phase of Medicine Flow. I'', 4, 2(3), (3)4.
- 19041 Pumice, rhyolitic. Obsidian Group, Pumice Stone Mountain. I, 4, 2, 3(4).
- 19044 Obsidian, trachytic. Massive Lava Group, north slope Medicine Lake Highland. I, 4, "2, 3(4).
- 19103c Obsidian, rhyolitic. Obsidian Group, Big Glass Mountain. I, 4, 2, 3(4).
- 19103b Obsidian, rhyolitic. Obsidian Group, Big Glass Mountain. I, 4, 1(2), 3''.
- 19103 Obsidian, rhyolitic. Obsidian Group, Big Glass Mountain, Herdsman analysis, I, 4, "2, 3''. Shepherd analysis, I, 4, "2, 3(4).
- 19033a Obsidian, rhyolitic. Obsidian Group, Little Glass Mountain. I, 4, "2, 3''.
- 19007 Obsidian, rhyolitic. Massive Lava Group, south slope Medicine Lake Highland. I, "4, (1)2, 3.

ON BABINGTONITE

CHARLES PALACHE AND F. A. GONYER

SUMMARY

Babingtonite from four new localities, all in Massachusetts, is described. Four new chemical analyses show an extraordinarily constant composition and lead to the formula $\text{Ca}_2\text{Fe}''\text{Fe}'''\text{Si}_6\text{O}_{14}(\text{OH})$. The form and optical and other physical characters are shown to be essentially identical in all occurrences. Reasons are given for regarding babingtonite as not belonging either to the pyroxene group, the "triclinic pyroxene" group, or the feldspar group of minerals in all of which it has been at one time or another classified. Rather it is to be considered as standing quite alone and without near relatives. Its paragenesis is discussed and it is shown to be characteristically a low temperature hydrothermal mineral.

TABLE OF CONTENTS

NEW OCCURRENCES IN MASSACHUSETTS.....	295
Winchester Highlands.....	295
Holyoke.....	296
Deerfield.....	298
Uxbridge.....	298
CHEMICAL COMPOSITION.....	299
New analyses.....	299
Formula.....	299
Place in classification.....	300
PHYSICAL CHARACTERS.....	301
PARAGENESIS.....	301

The study of some new or hitherto undescribed occurrences of babingtonite has once more brought up the question of the place in the mineral classification of this rather uncommon mineral. In the following pages it is proposed to give an account of the results of this investigation.

NEW OCCURRENCES IN MASSACHUSETTS

BABINGTONITE FROM WINCHESTER HIGHLANDS, MASS. Winchester Highlands lies a few miles north of Cambridge on the border of the Boston Basin. A large quarry for road metal has been operated there for some years at the base of Blueberry Mountain and in it a number of interesting mineral deposits occur. The principal rock quarried is a granodiorite together with the quartzite into which it has been intruded. Cutting the diorite are lense-like intrusions of granite pegmatite and a later system of narrow veins cutting both diorite and pegmatite. The pegmatite is of an

unusual type with much original epidote and such rare-earth minerals as allanite and thorite (1).

The veins are generally but a few inches wide, often mere seams, and have no great linear extent. They are for the most part wholly filled with calcite but some of them show a variety of earlier minerals when the calcite has been removed by weathering or by solution in acid. These include prehnite, epidote, babingtonite, albite, quartz, hornblende (a fibrous variety), several zeolites and sulphides in small amount.

Babingtonite is sometimes the first mineral to form, attached directly to the vein wall; where prehnite is present babingtonite rests upon that and may be followed by a later generation of prehnite and by the zeolites heulandite and chabazite and always by calcite. The crystals are rarely more than a few millimeters in dimension, often doubly terminated, and are brilliant black in color. The prism zone is dominant and by its prominence and the striations on some of its faces may always be recognized. A number of crystals were measured and were found to conform closely in habit and angles to the babingtonite crystals from Somerville, described by Palache and Fraprie (2).

The forms observed were $c(001)$, $b(010)$, $a(100)$, $h(110)$, $g(2\bar{1}0)$, $f(\bar{3}20)$, $k(1\bar{1}0)$, $o(011)$, $s(0\bar{1}1)$, $d(101)$, $n(\bar{1}01)$, $p(111)$, $q(\bar{1}\bar{1}1)$ and the new form $r(1\bar{1}1)$. $q(\bar{1}\bar{1}1)$ was first observed by Watanabé (3) on the Japanese babingtonite.

	Calculated		Observed		Number of Observations
	ϕ	ρ	ϕ	ρ	
$q(\bar{1}\bar{1}1)$	$-34^{\circ} 35'$	$40^{\circ} 22'$	$34^{\circ} 16'$	$40^{\circ} 15'$	3
$r(1\bar{1}1)$	142 07	45 03½	141 20	45 07	1

Figures* 1 and 2 show the new form and typical habits.

The optical characteristics were identical with those stated for the mineral by Washington and Merwin (5).

The chemical analysis and formula will be discussed on a later page.

BABINGTONITE FROM HOLYOKE, MASS. This locality was first discovered within a year or two and was brought to the writer's attention by Dr. H. O. Hastings of Holyoke who generously donated to the Museum his finest specimens and conducted us to the locality where an abundance of material was collected. It occurs

* These and the following crystal figures were drawn by L. W. Lewis and Edgar Mendelsohn.

in a quarry opened recently in the diabase at the foot of Mt. Tom, a few hundred yards from the foot of the incline railway which runs to the top of that mountain. It occurs with prehnite and calcite in gash veins traversing the diabase. Openings in the vein are coated with masses of the brilliant black crystals which are grouped in radiated masses or implanted singly on prehnite surfaces. Single crystals reach a length of 3 cm. and surfaces of a square foot or more are wholly covered by it in splendid groups. In abundance and beauty it far surpasses any previously described occurrence of babingtonite.

The crystals are of simple form and poorly suited for crystal measurement as they are deeply striated and are generally in sub-parallel aggregates so that the crystal faces give multiple reflexions. The forms of the prism zone are dominant, especially the prisms $f(3\bar{2}0)$ and $g(2\bar{1}0)$. Other forms observed as shown in the figure are: $a(100)$ $b(010)$ $h(110)$ and $k(110)$. The termination is either by the base, $c(001)$, alone or with one or both of the forms $o(011)$ and $d(101)$. Figure 3 shows a typical habit.

The physical and optical characters of this babingtonite agree so closely with those of Arendal that they may be said to be identical. The analysis is discussed below.

A peculiar alteration is shown by some specimens of the Holyoke babingtonite. A mass of parallel fibres of silvery white color begins to grow outward from the surface of a babingtonite crystal. The axis of the bundle of fibres does not have, so far as could be observed, any particular orientation with respect to the underlying crystal but it is constant for all the fibres on any one crystal. In a few cases these fibres were seen to be embedded in a later growth of calcite and this halted the process of their formation so that the babingtonite is not visibly destroyed. Generally, however, the fibrous growth penetrates the crystal from both sides and invades it almost to the centre leaving only a narrow black band of unaltered material from which the fibres seem to spring. The fibres in turn change from the original silvery-white form to brown and then to rusty limonitic phases. Mr. Berman made an optical examination of the fibres on the Federof stage and established their probable nature. They appear to be a pyroxene, probably augite; the fibres are excessively fine however, and yielded no characteristic cross sections or cleavage.

Refractive indices

$$\left. \begin{array}{l} \alpha = 1.700 \\ \beta = 1.710 \\ \gamma = 1.725 \end{array} \right\} \pm .003$$

$$Y = b? \quad Z \wedge c = 43^\circ$$

$$Bx (+). \quad 2V = 50^\circ \pm 2^\circ$$

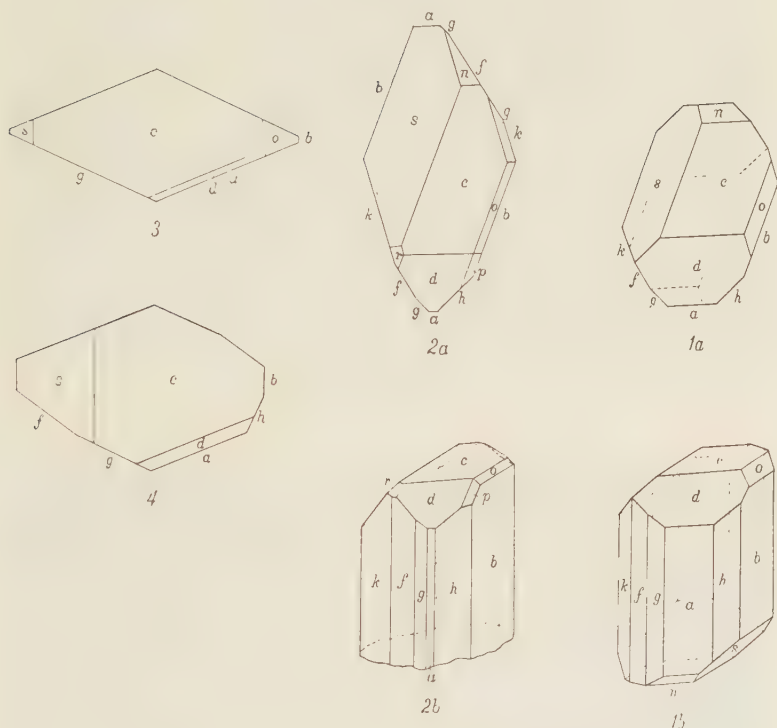
The calcite associated with this babingtonite is in part in large brownish rhombohedrons, too rough for measurement but apparently near the negative rhombohedron (0221); in part in slender (later) crystals with scalenohedral termination. Chabazite was noted in a few small rhombohedral crystals. Natrolite forms spheroids or rosettes of slender glassy needles in a few specimens. Quartz, white or amethystine, is sparingly present and a few minute pyrite crystals were seen in one specimen. Datolite was present in one specimen only.

BABINGTONITE FROM DEERFIELD, MASSACHUSETTS. In his description of the Deerfield Dike and its minerals, Emerson (4) mentions the occurrence of crystals of black axinite. The writer long since secured specimens of this supposed axinite and identified it as babingtonite but this determination has not been published. The vein specimen was freed from calcite with acid and revealed very rough and imperfect crystals of babingtonite resting on or embedded in prehnite. The forms $a(100)$, $b(010)$, $g(210)$, $d(101)$, and $o(011)$ were identified on minute crystals of the habit of figure 3. Sufficient material was obtained from one of the specimens for a chemical analysis as shown on a later page.

BABINGTONITE FROM UXBRIDGE, MASSACHUSETTS. A small quarry was opened in Uxbridge, Mass. many years since, in gneiss. Cutting the gneiss were small gash veins of granite pegmatite from the cavities of which a small collection of crystallized minerals was made. The minerals comprise microcline, albite in pericline habit, adularia, epidote, biotite altered to chlorite, quartz, heulandite, prehnite, pyrite and babingtonite.

The babingtonite crystals are not numerous and were too much altered to permit of analysis. The crystals which reach a diameter of four or five millimeters are simple, showing the forms $c(001)$, $b(010)$, $a(100)$, $h(110)$, $g(2\bar{1}0)$, $f(3\bar{2}0)$, $s(0\bar{1}1)$, $o(011)$ and $d(101)$ as shown in figure 4. The occurrence is chiefly interesting as adding one more to the very numerous localities of this mineral in Massachusetts. An additional interest attaches to the Alpine habit of the veins and constituent minerals. The gneiss is a "pencil gneiss" showing pronounced linear structure. The pegmatite veins fill ten-

PLATE I



Crystals of Babingtonite from Massachusetts Localities.

FIGS. 1a and 1b. Babingtonite from Winchester Highlands. Plan and clinographic projection of a doubly terminated crystal showing the forms $c(001)$, $b(010)$, $a(100)$, $h(110)$, $g(2\bar{1}0)$, $f(3\bar{2}0)$, $k(1\bar{1}0)$, $o(011)$, $s(0\bar{1}1)$, $d(101)$, $n(\bar{1}01)$.

FIGS. 2a and 2b. Babingtonite from Winchester Highlands. Plan and clinographic projection of a crystal showing the forms of figure 1 and in addition $p(111)$, $q(\bar{1}\bar{1}1)$ and $r(\bar{1}\bar{1}1)$.

FIG. 3. Babingtonite from Holyoke. Plan of a prismatic crystal showing the forms $c(001)$, $b(010)$, $a(100)$, $g(2\bar{1}0)$, $o(011)$, $s(0\bar{1}1)$, and $d(101)$.

FIG. 4. Babingtonite from Uxbridge. Plan of a crystal showing the forms $c(001)$, $b(010)$, $a(100)$, $h(110)$, $g(2\bar{1}0)$, $f(3\bar{2}0)$, $s(0\bar{1}1)$, and $d(101)$.

PLATE II

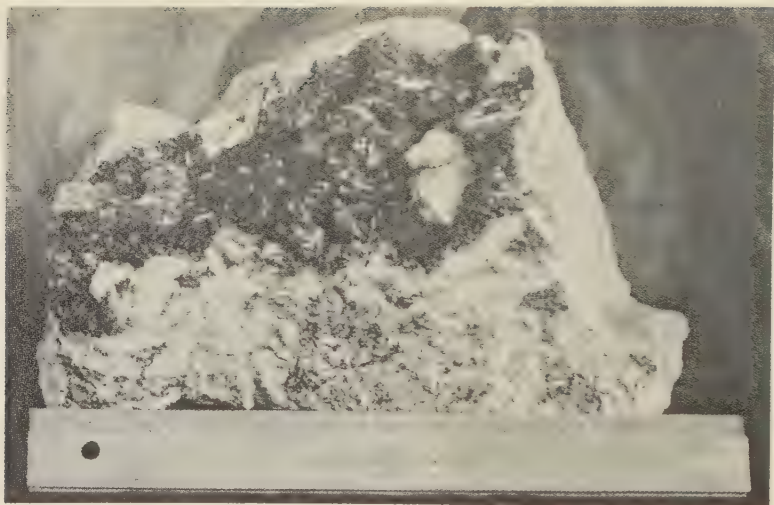


FIG. 5.



FIG. 6.

Photographs of Babingtonite from Holyoke, Mass.

The Babingtonite, black, rests on prehnite. Calcite crystals are later. The black linear markings in figure 6 are hollow prehnite casts of a mineral, probably anhydrite, now wholly removed by solution. Scale of inches.

sional cracks normal to the gneissic structure. The feldspars include adularia and pericline, both Alpine habits of this group of minerals. And the whole appearance of the small cavities strikingly recalls that of many Swiss "crevice" deposits.

CHEMICAL COMPOSITION OF BABINGTONITE

The three following analyses were made by Mr. Gonyer on abundant samples of very pure material prepared by Mr. Berman and Mr. Mendelsohn. Their identical nature can only be described as astonishing. With them is a new analysis by the same chemist of the Somerville babingtonite, correcting the figures obtained by Fraprie (2); and lastly the only other reliable modern analysis of the mineral from Arendal.

1. Babingtonite from Winchester Highlands analyzed by F. A. Gonyer
2. Babingtonite from Holyoke analyzed by F. A. Gonyer
3. Babingtonite from Deerfield analyzed by F. A. Gonyer
4. Babingtonite from Somerville, Mass., analyzed by F. A. Gonyer
5. Babingtonite from Arendal, analyzed by Washington and Merwin (5)
6. Babingtonite calculated from formula $\text{Ca}_2\text{Fe}''\text{Fe}''' \text{Si}_5\text{O}_{14}(\text{OH})$

	1.	2.	3.	4.	5.	6.
SiO ₂	52.46	52.44	52.40	52.12	52.80	52.41
TiO ₂	—	none	—	0.31	0.29	—
Al ₂ O ₃	0.19	0.23	none	0.08	2.41	—
Fe ₂ O ₃	14.74	14.43	14.40	13.56	13.17	13.93
FeO	9.32	10.12	10.09	10.78	7.68	12.52
MnO	1.21	1.03	1.13	0.76	1.89	—
MgO	0.95	0.65	0.47	0.60	0.92	—
CaO	19.73	19.67	19.71	20.44	19.19	19.57
Na ₂ O	0.14	0.08	0.21	0.09	0.48	—
K ₂ O	}	none				
H ₂ O						
	1.21	1.27	1.23	1.33	0.91	1.57
	99.95	99.82	99.64	100.07	99.74	100.00
Sp. Gr.*	3.368	3.369	3.340	3.342	3.359	

* Determined by Mr. Berman with the pycnometer.

The five analyses show essential identity in the composition of these samples of the mineral from widely separated localities and of various origins. They all lead to the same formula $\text{Ca}_2\text{Fe}''\text{Fe}''' \text{Si}_5\text{O}_{14}(\text{OH})$. The ratio of ferrous iron to ferric iron is constant and in the proportion of 1:1. When it was found that the babingtonite from Somerville, analyzed by Fraprie (2), was exceptional in having considerable alumina and in having more ferric iron than ferrous, new material was isolated and analyzed with the result shown in

Column 4 of the Table. It appears that Fraprie's analysis was in error and that in this occurrence also the usual proportion of iron oxides is present.

This formula differs essentially from that of any member of the pyroxene group in the ratio of bases to silica. Here it is 4 to 5, in all pyroxenes 4 to 4. In view of this fact and other arguments, summarized best by Washington and Merwin (5) it seems necessary to remove babingtonite from the pyroxene group notwithstanding the possibility of so orientating the crystals that a form similarity exists. In the same way the attempt by Hillebrand (6) to draw a parallelism with anorthite, considering babingtonite as an iron-anorthite, must be considered simply as bringing out an interesting coincidence of certain angles, not of any real significance in the nature of the mineral.

Gossner and Mussgung (7) have also considered this interpretation of babingtonite in the light of their measurements by x-ray study of the dimensions of a unit cell. Although an orientation is adopted by them differing from that here used (Dauber) they employ the same pinacoidal body and the formula $\text{Ca Fe Si}_2\text{O}_6 \cdot \text{SiO}_2$. They calculate four molecules in the unit cell. Our formula yields by the same calculation two molecules in the unit cell. Their effort to bring out an analogy between feldspar and babingtonite is unsuccessful. They revert to the pyroxene-like formula above given which is that of a pyroxene which has a molecule of silica built into it—a most unsatisfactory conclusion. Neither do they consider the hydroxyl always present. It seems safe to conclude that babingtonite can not in any proper sense be regarded as either a pyroxene or a feldspar.

Nor does it appear to belong to the group of so-called "triclinic pyroxenes." These all conform to the pyroxene ratio with bases to silica equal 1 to 1, and have close optical relations as shown by the recent work of Sundius (8). They have also common cleavage directions. If babingtonite is orientated to bring out similarity of angles, its cleavage is not similar to other members of the group and its optical orientation is quite unrelated. Sundius draws wollastonite into this group and Warren and Biscoe (9) show that wollastonite, despite its apparent monoclinic symmetry, is really triclinic and has a structure unrelated to the pyroxenes. Their study confirms that of Sundius in placing wollastonite in the "triclinic pyroxene" group which is not closely related to the pyroxene group in struc-

ture. The sharper classification of isomorphous groups now possible with the aid of structure analysis would seem to lead away from the older tendency to force into a single series minerals which both in form and composition are really fundamentally different. As far as babingtonite is concerned, it can not be said to have any group relationship as the facts now stand.

PHYSICAL CHARACTERS

The crystals of all known occurrences of babingtonite show strikingly little variation. The forms are not numerous and the common ones are the same everywhere. The only variable element is in habit, which varies from a dominant prismatic development, to one of tabular form parallel to the basal pinacoid. This is most pronounced in babingtonite from Baveno, less so in that from Uxbridge. As these are both pegmatite occurrences it is safe to say that the unusual habit is a function of the different paragenetic conditions.

The optical constants of babingtonite are as similar in all known occurrences as is the chemical composition, strengthening the impression that this is a strongly individual mineral and not a member of a variable isomorphous series.

PARAGENESIS

In Table I are collected the facts regarding the known authentic* occurrences of babingtonite both as to geologic character and associated minerals. It will be seen that on the whole the accompanying minerals are very similar notwithstanding a considerable variety of origin. Babingtonite has been found in iron skarns, in granite pegmatites and in hydrothermal veins, especially those traversing diabase. In all of these occurrences but one, the contact ores of Japan,

* Certain supposed occurrences of babingtonite are here purposely omitted. That from Devonshire, England, whose analysis is given by Dana, SYSTEM 1892, p. 382, appears when critically examined to be a pyroxene. The original description by Forbes (*Phil. Mag.*, 37, 328, 1869) gives no physical characters and the occurrence, stated as a large mass of material, so pure as to have been mined as an iron ore, recalls rather a contact deposit of pyroxene than any known babingtonite deposit. The Scotch occurrence described by Heddle (*Min. Mag.*, 5, 147, 1883) in a granite pegmatite is also inadequately described but from the analysis appears to be a pyroxene. The "babingtonite-like" mineral from Broken Hill Mine, New South Wales, described by Stillwell (in Andrews', E. C., *Geology of Broken Hill District*, Appendix II, p. 386) is certainly, from the analysis and optical characters, a lime-rich rhodonite.

babingtonite is a late mineral in the sequence, and often the last to form with the exception of calcite. Epidote, prehnite and zeolites are characteristic associates, one or both found in almost every deposit. It is essentially a low temperature, hydrothermal mineral, judged by its paragenetic history. And here again it may be said to show a character essentially opposed to that of any typical pyroxene.

TABLE I
PARAGENESIS OF BABINGTONITE

Locality	Type of Deposit	Associated Minerals
Arendal, Norway	Contact Iron Skarn	Hornblende, garnet, epidote, oligoclase, albite, calcite.
Nassau, Germany	Contact Diabase and slate	Ilvaite, beudantite, jasper, calcite.
Yakubi Mine, Japan	Contact of granodiorite with slate and limestone	Hedenbergite, garnet, magnetite, sphalerite, chalcopyrite, quartz, calcite, ilvaite?
Baveno, Italy	Pegmatite Granite	Microcline, albite, quartz, epidote, tourmaline, zeolites, calcite, hematite.
Uxbridge, Mass.	Pegmatite Granite	Microcline, adularia, epidote, biotite, hornblende, quartz, heulandite, pyrite.
Athol, Mass.	Veins in chloritic gneiss	Epidote, prehnite, pyrite
Buckland, Mass.	Veins in gneiss	Epidote, natrolite, chabazite, quartz, calcite.
Paterson, N. J.	Cavities in amygdaloidal diabase	Prehnite, quartz, calcite, datolite, zeolites.
Winchester Highlands, Mass.	Veins in diorite and granite pegmatite	Prehnite, epidote, albite, quartz, hornblende, zeolites, calcite.
Somerville, Mass.	Veins in diabase	Prehnite, quartz, epidote, chlorite, pyrite, chabazite, calcite.
Holyoke, Mass.	Veins in diabase	Prehnite, quartz, calcite, datolite, chabazite, natrolite, pyrite.
Deerfield, Mass.	Veins in diabase	Prehnite, chlorite, calcite, datolite.

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1. Dr. A. C. Lane has described his experiments on the radioactivity of this rock and its probable age in *Ann. Rept. Nat. Res. Coun.*, **1927-28**, Appendix F, 507.
2. Palache and Fraprie, Babingtonite from Somerville, Mass.: *Am. Acad. Arts & Sci. Proc.*, **38**, 383, 1902.

Numerous errors in form symbols appear in this paper as follows:

Page 387 in list of forms by various authors.

Col. 2 fourth line from bottom (221) should read (22T)

Col. 2 last line (221) should read (2 $\bar{2}$ 1)

Col. 5 fourth line from bottom (551) should read (5 $\bar{5}$ 1)

Col. 6 first line (011) should read (0 $\bar{1}$ 1)

Page 389, Table II

Col. 1 $f(320)$ should read $f(3\bar{2}0)$

$k(110)$ should read $k(1\bar{1}0)$

$s(011)$ should read $s(011)$

3. Watanabé, M. On the Babingtonite from the contact metamorphic deposits of the Yakuki Mine, Japan: *Am. J. Sc.*, **4**, 159, 1922.

In the table of angles of new forms described in this paper, p. 160 there are several errors as follows:

	ϕ	ρ	ϕ	ρ
$j\bar{1}02$ read $-127^{\circ}08'$		$14^{\circ}37\frac{1}{2}^{\circ}$ instead of $-127^{\circ}07'$		$14^{\circ}39'$
$l\bar{2}01$ read $-115\ 34\frac{1}{2}$		$48\ 50$ instead of $-115\ 26$		$49\ 59$
$q\bar{1}11$ read $-34\ 35$		$40\ 22$ instead of $-34\ 17$		$40\ 25$

4. Emerson, B. K., The Deerfield Dike and its Minerals: *Am. J. Sc.*, **24**, 350, 1882
U. S. G. S. Bull. **126**, 31, 1894.
5. Washington, H. S. and Merwin, H. E., On Babingtonite: *Am. Min.*, **8**, 215, 1923.
6. Hillebrand, S., Ueber Aegirin und Babingtonit: *Tsch. Min. Mitth.*, **32**, 256, 1913.
7. Gossner, B. und Musgnug, F., Ueber die systematische Stellung von Neptunit und Babingtonit: *Centb. für Min.*, A, **1928**, 274.
8. Sundius, N., On the triclinic manganiferous pyroxenes: *Am. Min.*, **16**, 411-429, 488-518, 1931.
9. Warren, B. E. and Biscoe, J., The crystal structure of the monoclinic pyroxenes: *Zeit. für Kryst.*, **80**, 391, 1931.

ZUNYITE FROM GUATEMALA

CHARLES PALACHE

The mineral zunyite is so rare in nature that any information regarding a new occurrence of the mineral seems worthy of record. The following observations gain an added interest perhaps from the unusual circumstances surrounding the discovery of this occurrence.

The excavations of the ruined Maya city of Uaxactun, situated in the plains of northern Guatemala just north of Lake Peten, have been conducted by the Carnegie Institution during the last few years. One of the archeologists in charge of the investigations, Dr. Oliver Ricketson, Jr., brought to the Harvard Mineralogical Laboratory powders which had been taken from pots buried in graves opened during the excavation at Uaxactun. He desired a mineralogical examination of these eight powders of which small samples were submitted, and this the writer undertook. Some of them contained fresh-water shells and in addition a grayish powder which proved to consist largely of calcite. This was interpreted as a limestone spring-deposit or sinter probably introduced into the pots after burial. When the calcite, which varied in different samples from a very small to a very large part of the whole, was removed with dilute acid there remained a small amount of clay material and a brilliant metallic residue which proved to consist very largely of minute crystals of hematite. Most of the powders also contained hematite in the form of a deep red ochre. A further concentration of the residues with the magnet revealed a small nonmetallic fraction consisting of extremely sharp individual crystals of tetrahedral form which, on optical investigation, proved to be the mineral zunyite.

Before describing the hematite and zunyite in detail a few speculations may be permitted on the possible origin of this material and the means by which it reached the place where found. The material is certainly not in any sense a sand since none of the constituents show conspicuous water wear. Both hematite and zunyite are in sharp, brilliant crystals. The hematite is in characteristic scales which are of a habit most familiar in volcanic fumerole deposits; while zunyite has not heretofore been found in such deposits it is elsewhere known as a contact mineral and is related to igneous sources. It seems to be fairly certain that these powders were col-

lected at some volcanic vent possibly because of their brilliant spangled nature or to be used as red pigments and that they may have been deposited in these graves as votive offerings, valuable because of their distant origin. The nearest volcanoes which might have served as a source for the material are far to the south in Guatemala and San Salvador. It so happens that there are in our collections samples of crystalline hematite collected at the volcano Laguna Verde in San Salvador, which are entirely similar to that material in these powders. This volcanic region then is probably the source of the material.

Mr. Ricketson states in a letter:—"The red pigment you describe as derived from powdered hematite is extremely common in graves and used as paint. Often one sees a red hand on plastered walls etc. made by immersing the actual hand in red paint and pressing it on the wall.

As Uaxactun lies very nearly in the geographic center of the Yucatan peninsula, substances of volcanic origin must of necessity have been brought from the Highlands of Guatemala at the nearest. Obsidian is of very common occurrence, but always in cores or chips or finished implements. Granite mauls are also fairly common. Their flint, however, was probably derived from flint nodules, very common in the local limestone throughout the peninsula."

HEMATITE

The hematite crystals are excessively flat scales, parallel to the basal plane (0001). Very rarely do they exceed a millimeter in diameter and vary from this down to mere dots much less than 0.1 mm. The vast majority are perfect crystals without fracture and show in outline hexagonal, trigonal, or sometimes rectangular forms according to the particular development of the faces bounding the edges of the plates. The basal planes are generally perfectly devoid of striations but in some plates there is a faint trigonal striation and in certain of the scales a number of plates are grouped as subparallel aggregates. In addition to these brilliantly lustrous crystals there are a few scales which are dull due to a thin coating of ochreous hematite. On examination with the goniometer the crystals all show practically the same habit. They are combinations of the forms $c(0001)$, $r(10\bar{1}1)$, $e(01\bar{1}2)$ and $n(22\bar{4}3)$, but the scales are so thin that the forms other than c are all reduced to mere lines on the plate edges. A few minute octahedrons of magnetite are also found in the magnetic fraction.

ZUNYITE

The zunyite crystals are minute, the largest as much as 1 mm. in diameter, the average about 0.1 mm. and many of them mere dots. All are marvelously sharp in outline and regularly developed; rarely are two crystals attached to one another but in a few of them hematite scales are embedded, proving the simultaneous formation of the two minerals. The color varies from clear white to opaque white, dull pink and red, the latter doubtless due to inclusion of ochreous hematite.

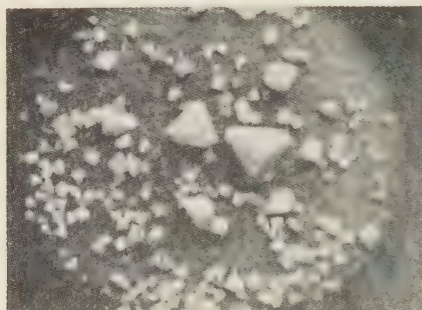


FIG. 1. Photograph of crystals of Zunyite. Magnification about 8 diameters.

The forms present are the cube (100) and the tetrahedrons, positive and negative, (111) and ($\bar{1}\bar{1}\bar{1}$). These are present in every possible relative proportion:—simple tetrahedrons; the same with line truncations of their edges by the cube and barely visible facets of negative tetrahedron; cubes with equal or unequal truncation of the corners by both tetrahedrons; in short they present under the binocular a complete series of gradations of fascinating variety. The photograph, figure 1, gives but an inadequate picture of this endless variation. Amid the thousands of tiny crystals were seen two or three perfect interpenetration twins like those recently described by Spencer. With the zunyite in this fraction of the powder were a few quartz crystals, doubly terminated, of the simple form characteristic of high-quartz; and a few brilliant crystals of zircon. An occasional minute grain of dark color proved to be tourmaline.

A sample of the zunyite crystals was purified by means of heavy solutions. About 0.5 grams was obtained and was analyzed by Mr. Gonyer with the result shown below.

For comparison and to show how constant is the composition of this mineral in its three known widely separated localities two other recent analyses of zunyite are also given.

I. Zunyite from Guatemala. F. A. Gonyer, Analyst.

II. Zunyite from the Zuni Mine, Colorado. B. Gossner und F. Mussnug, *Centralb. für Min.*, A, 1926, 149.

III. Zunyite from Postmasburg, So. Africa. L. T. Nel, *Min. Mag.*, 22, 1930, 214. H. G. Weall, Analyst.

IV. Composition calculated for $\text{Al}_8\text{Si}_3\text{O}_{12}(\text{OH} \cdot \text{F} \cdot \text{Cl})_{12}$.

	I	II	III	IV
SiO_2	25.10	24.15	24.25	25.32
Al_2O_3	57.23	57.68	56.75	57.29
Fe_2O_3	1.58	0.18	1.3	
MgO	—	—	0.4	
CaO	—	—	0.35	
Na_2O	0.18	0.31	1.65	
K_2O		0.18	tr	
Cl	2.75	2.90	3.5	2.99
F	5.43	5.19	0.5	6.40
P_2O_5	0.53	0.52	0.25	
H_2O	10.61	11.12	11.40	11.37
$\text{H}_2\text{O} -$		—	0.4	
	<hr/> 103.41	<hr/> 102.23	<hr/> 100.75	<hr/> 103.37
Less O for Cl, F	2.90	2.83	1.00	3.37
	<hr/> 100.51	<hr/> 99.40	<hr/> 99.75	<hr/> 100.00
Sp. Gr.		2.878	2.88	

The formula derived from this analysis is:



This is the formula given by Hillebrand originally and used in a modified form by Groth. A summary of recent discussions of the formula of zunyite may be found in the paper of Dr. Nel from which analysis No. III was taken. The writer feels that until a complete structure analysis of the mineral is worked out the above empirical formula suffices as well as any to express its composition.

THE CHEMICAL NATURE OF JOAQUINITE

CHARLES PALACHE AND W. F. FOSHAG

SUMMARY

Composition $\text{NaBa}(\text{Ti,Fe})_3\text{Si}_4\text{O}_{15}$.

Crystallography: orthorhombic; forms: $c(001)$, $p(111)$, $m(110)$.
 $a:b:c=0.919:1:2.14$. $a=9.61\text{\AA}$, $b=10.45\text{\AA}$, $c=22.4\text{\AA}$.

Physical Properties: $\alpha=1.748$, $\beta=1.767$, $\gamma=1.823$. Bx (+). $2V=50^\circ \pm .p < v$.
 $X=a$, $Y=b$, absorption $Z>Y>X$. $G.=3.89$. $H=5\frac{1}{2} \pm$. Color, honey yellow to brown.

The mineral joaquinite was first recorded by Louderback* in 1909. It occurs in minute amounts associated with benitoite and neptunite in the unique deposit of these unusual titanosilicates in San Benito County, California. Scarcity of material made it impossible for Louderback to make any but microchemical tests on the tiny crystals and he supposed joaquinite to be a titanosilicate of calcium, possibly a dimorphic form of titanite. It was correctly designated as orthorhombic in crystallization but nothing has since been added to the original incomplete description.

Sufficient material for a fuller investigation was finally secured by working over large amounts of material from this locality. The veins containing the associated minerals are filled in large part by massive natrolite. Several hundred pounds of the vein material was secured and subjected to the action of hydrochloric or sulphuric acid to dissolve the natrolite. This laborious process yielded specimens with variable amounts of neptunite and benitoite and about 10 per cent of them showed more or less joaquinite. By scraping off every visible crystal and by collecting and washing the gelatinous sediment in the acid jars, something less than a gram of pure material was finally obtained. It may be said in passing that the thousands of crystals of benitoite and neptunite revealed on these specimens added no new facts regarding their crystallography to those already described.

The joaquinite crystals are always small, the largest seen measuring not more than 2 mm. in maximum diameter. They are generally attached to the wall of the vein, like the majority of neptunite and benitoite crystals; but a few were completely enclosed in the natrolite and in one or two cases were implanted on or surrounded by benitoite. The three titanium minerals then show no

* Louderback, G. D., Benitoite: *Bull. Univ. of Calif., Dept. of Geology*, **5**, 1909, 376.

marked sequence in time of deposition. Isolated crystals are the rule; the specimen shown in the photograph, fig. 2, was the only one of several hundred obtained which showed more than an occasional crystal.

Joaquinite is orthorhombic, showing only the forms $c(100)$, $p(111)$, and rarely $m(110)$. The habit varies from pyramidal with a tiny facet of the base, to flat tabular parallel to the base as shown in the two figures.

The crystals are always striated and are often in subparallel aggregates; so that although hundreds of crystals were examined none was found which gave satisfactory signals on the goniometer, images being multiple or confused. By selecting the brightest image of the chain of signals which often extended over several degrees of ρ angle the following fairly consistent readings were obtained on three crystals:

TABLE I
ANGLES OF JOAQUINITE

Crystal 1.	ϕ	ρ	Crystal 3.	ϕ	ρ
	47° 24'	73° 31'		47° 17'	73° 20'
	26	33		19	24
	14	39		13	19
	46 57	40		11	55
			Average	47 17	73 27
Crystal 2.	47 16	73 12			
	20	21			
	15	16			
	13	29			

Taking this form as (111) the coordinate angles yield the elements

$$p_0 = 2.47 \quad q_1 = 2.28$$

$$a:b:c = 0.923:1:2.28$$

Another axial ratio was obtained by the measurement of unit cell dimensions from x -ray photographs which were obtained by the rotation of crystals about each of the three crystallographic axes. The range of values obtained is shown in Table II.

TABLE II.

For the a -axis rotation		For the b -axis rotation	
Layer line	Axis length (Å)	Layer line	Axis length (Å)
1	9.72	2	10.6
2	9.86	3	10.6
3	9.58	4	10.4
4	9.58	5	10.4
5	9.47	6	10.3
6	9.58	7	10.3

For the c -axis rotation	
Layer line	Axis length (Å)
1	22.9
2	22.9
3	22.9
4	22.2
5	22.2
6	22.2
7	22.2
8	23.7
9	22.2
11	22.9

The weighted average values thus derived are:

axis $a = 9.61$ Å; axis $b = 10.45$ Å; axis $c = 22.4$ Å from which are calculated

$$p_0 = 2.33 \quad q_0 = 2.14$$

$$a:b:c = 0.919:1:2.14$$

Calculating coordinate angles for (111) from these axes we obtain

$$\phi = 47^\circ \quad 25' \quad \rho = 72^\circ \quad 29'$$

By measurement

$$\phi = 47^\circ \quad 17' \quad \rho = 73^\circ \quad 27'$$

The agreement is good for ϕ but very poor for ρ . Since the x -ray values are based on a larger number of measurements which are in this case at least as accurate as those obtained by goniometric methods, the latter values are adopted.

PHYSICAL PROPERTIES

The indices of refraction and other optical properties were measured by the immersion method with the following results:

$$\alpha = 1.748 \quad (+) 2V = 50^\circ$$

$$\beta = 1.767 \quad \rho < \nu \text{ perceptible}$$

$$\gamma = 1.823$$

The orientation is as given by Louderback

$$X = a, Y = b, Z = c$$

Absorption in yellow slight with $Z > Y > X$.

Color, honey yellow to brown.

The density as measured by floating in Clerici solution is 3.89.

Applying the formula $\frac{n-1}{d} = K$ to joaquinite there is apparently a large discrepancy between the K value as determined from

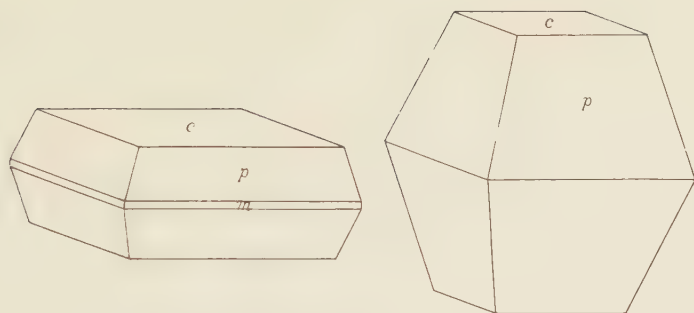


FIG. 1. Crystals of Joaquinite, San Benito Co., Calif.

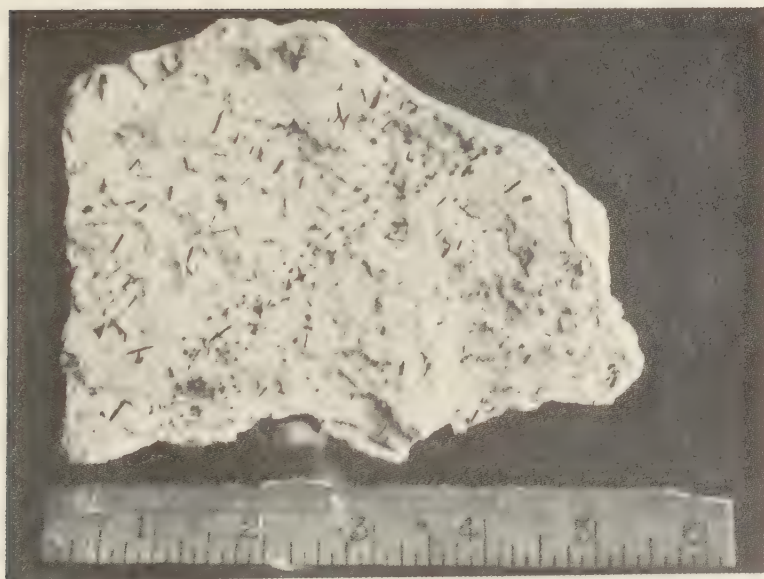


FIG. 2. Photograph of a specimen of joaquinite. The black dots are joaquinite crystals, the needles neptunite, the triangular crystals, benitoite. San Benito Co., Calif.

the physical constants, and the value as determined from the composition.

$$\text{For } \frac{n-1}{d} = K = \frac{.775}{3.89} = .199$$

whereas K from the composition is .244. This large discrepancy can not be ascribed to error in determination of either n , the mean index of refraction, or d , the density, since these two values are determinable well within the limit of error indicated. It seems improbable that the refractive energy constants (K) used in this computation are much in error since an application of this law to benitoite, which contains essentially the same oxides, yields a satisfactory agreement. There are left then the possibilities that the titanium oxide, as given in the analysis, is really in another state of oxidation and consequently has a different K value, or that some rare element with a fairly low K value (0.265) is present in joaquinite, and has been determined as TiO_2 , due to the very small sample available for analysis.

COMPOSITION OF JOAQUINITE
Analyses by W. F. Foshag

	I	II	III	IV	V
SiO_2	37.37	35.27		36.4	36.3
TiO_2	32.03	29.53		30.5	32.0
FeO	3.17	3.41		3.5	3.8
BaO	23.13	23.91		24.7	23.2
CaO	0.29	0.27			
MgO	0.39	0.07		.3	
Ign.	0.91	0.47			
Na_2O			4.47	4.6	4.7
				100.0	100.0

- I. Preliminary qualitative-quantitative analysis, 0.2071 grams.
- II. Analysis on 0.1500 grams, FeO on 0.1012 grams.
- III. Average of 2 samples, 0.1016 grams and 0.1698 grams.
- IV. Average composition computed from II and III reduced to 100 per cent.
- V. Calculated from formula $\text{Na Ba (Ti, Fe)}_3 \text{Si}_4\text{O}_{15}$.

THE NUMBER OF MOLECULES IN THE UNIT CELL

From the axial lengths determined by rotation x -ray photographs, the volume in the unit cell is found to be $(9.61 \times 10^{-8}) \times (10.45 \times 10^{-8}) \times (22.4 \times 10^{-8}) = 2250 \times 10^{-24}$.

Substituting this in the relation

$$mM = dV$$

where m = number of molecules in unit cell

$$M = \text{molecular weight} \times (1.65 \times 10^{-24})$$

$$d = \text{density, } 3.89$$

$$V = \text{volume of unit cell} = 2250 \times 10^{-24}$$

for $M = 1324 \times (1.65 \times 10^{-24})$ in the formula $\text{Na Ba (Ti, Fe)}_3\text{Si}_4\text{O}_{15}$ the value for $m = 4$. There are, therefore, 4 molecules of composition $\text{Na Ba (Ti, Fe)}_3\text{Si}_4\text{O}_{15}$ in the unit cell of joaquinite.

The somewhat unsatisfactory results of this investigation of joaquinite, due at least in part to the small amount of material secured, seem disproportionate to the large amount of work involved. The senior author feels it his duty to give credit to his co-workers whose efforts made the study possible. The first lot of material worked was secured by Mr. Wilke of Palo Alto who made the long trip to the mine to collect it. The seventy-five pounds of vein specimens he shipped to us in 1927 was worked up by Lyman W. Lewis who spent several weeks treating it with acid, repeatedly washing away the gelatinous silica set free from the natrolite by the acid and then collecting and purifying the few crystals obtained. The fruit of his labor was 0.7 grams of nearly pure material and the analysis of this first sample was not satisfactory. The writer visited the locality in 1929 and shipped back another lot of about 200 pounds of specimens. These in turn were treated by Mr. Ber-
man with a like expenditure of weeks of labor and a product of 0.3 grams of pure material. He also made the x-ray study of the crystals and did part of the crystal measurement.

PLATE I

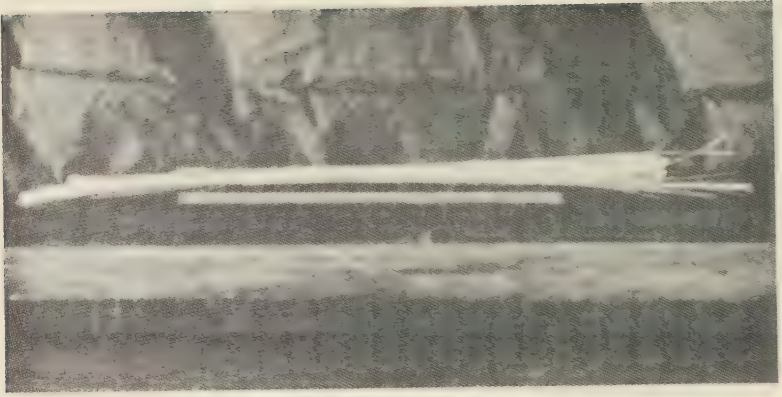


FIG. 1. Photograph of fibrous brucite from Asbestos, Quebec.

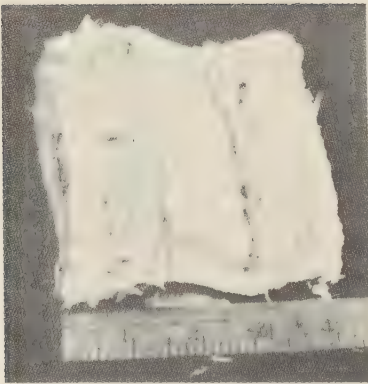


FIG. 2. Fibrous brucite in vein of chrysotile asbestos, Asbestos, Quebec.

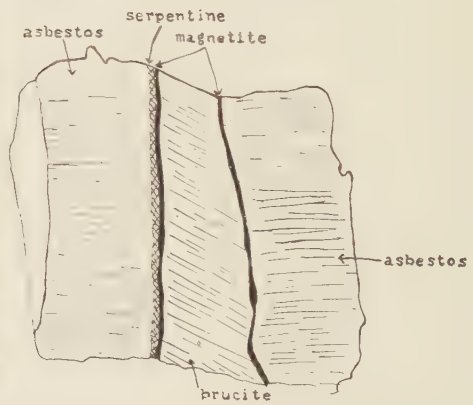


FIG. 3. Sketch of photograph in Fig. 2, to show the mineral relations.

FIBROUS BRUCITE FROM QUEBEC

HARRY BERMAN

WITH A NOTE ON ITS STRUCTURE AFTER DEHYDRATION

C. D. WEST

During a recent visit to the Johns-Manville Mine at Asbestos, Quebec, specimens of two unusual types of brucite were obtained. One consisting of long parallel fibres occurred in a crush zone, together with chrysotile, in the peridotite. The second, which was not seen in place, consists of a central zone of brucite in a vein of cross-fibre asbestos. Since these two forms of brucite differ somewhat in their properties they will be separately described.

The brucite occurring in the "slip-fibre" zone consists of parallel aggregates of fibres reaching a length of 20 inches. (Plate 1, fig. 1.) In the field the brucite is distinguished from the chrysotile with which it is associated by a greater hardness, and a greater ease of splitting along the whole fibre length. Further, the thin strands are lath like, even in minutest cross-section. A chemical analysis, by F. A. Gonyer, of this laboratory, follows:

FE-BRUCITE (NEMALITE) FROM ASBESTOS, QUEBEC

	Per cent	Molecular ratio	Magnetite
Fe ₂ O ₃	1.95	0.012	0.012
FeO	9.57	0.133	1×1.618
MgO	60.33	1.497	
H ₂ O	28.60	1.588	1×1.588
	100.45		

Mg:Fe=25:2

The material, as seen from the analysis, corresponds in composition to an iron-bearing brucite, which in this fibrous form is known as nemalite. No previous record of such long fibres of this material has been found.

Under the microscope the lath-like fibres, when not distorted, give parallel extinction along the fibre direction, indicating that the individual crystals have parallel orientation with respect to the fibre length. Further, the fibres show negative elongation so that the long direction can not be the *c*-axis of brucite, since that mineral is uniaxial positive. If the direction normal to the laths (*Z* of fig. 4) be considered the *c*-axis of brucite then a uniaxial positive interference figure should be seen on the lath face. Actually a fairly

well centered biaxial positive figure appears, with $2V$ about 70° . Assuming that the material is brucite, the anomolous axial angle may be explained as due to a subparallel aggregate of crystal laths. The laths must have parallel orientation with respect to the a -axis, i.e. the elongation; but the c -axis of the individual crystals have a maximum deviation of 2ϕ with each other. (Fig. 5.) A cross section

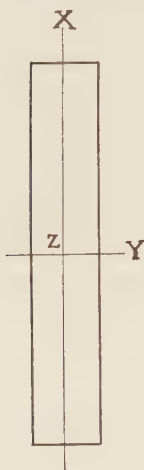


FIG. 4. Optical orientation in the brucite laths.

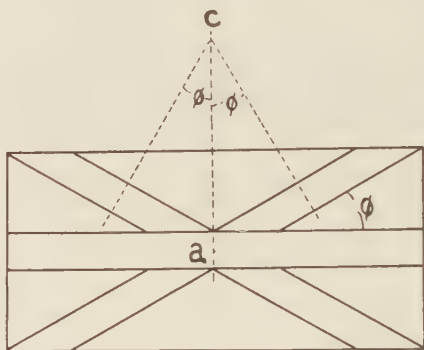


FIG. 5. Idealized cross-section through brucite fibers to show relation of individual crystals.

through an aggregate would show the orientation of the extreme individuals as given in figure 5. Referring to fig. 4, the refractive index in the direction Z is some value less than ϵ , and in Y is somewhat greater than ω , while $X = \omega$. The value $2V$ is then a function of the deviation of the individual laths from parallelism in the c -axis direction, i.e. $2V$ is a function of the angle ϕ which measures the maximum deviation of the c -axes of the individual laths making up the aggregate.

The birefringence of the aggregates is about half that of ordinary brucite plates. $\omega = 1.585$ along the fibre length. This high value for ω is consistent with the iron content of the material.

In order to test the validity of the assumptions based on the optical study of the fibres, an x-ray rotation photograph was made with the fibre axis as rotation axis, after which a Laue photograph was tried with the x-ray beam in the direction Z of fig. 4. The rotation photograph gave a sharp series of layer lines from which the

spacing along the fibre direction was computed as 3.16\AA , which is in agreement for the a axis spacing of brucite (3.13\AA). The sharpness of the lines further indicated that the individual crystals making up the aggregate were close to parallel in orientation along the a -axis. The lauegram proved to be identical with the rotation photograph, indicating that the aggregate is not in parallel orientation in the section across the elongation of the fibres. The x-ray evidence is thus in agreement with the assumptions made from the optical examination. The fibres are, then, made up of laths of brucite which differ from the normal platy habit in that one dimension of the plate is enormously extended in comparison with the others. The curious habit may be accounted for by the fact that the brucite has probably replaced the long "slip fibre" chrysotile asbestos, with which it is associated. The structural similarity of the a -axis direction of brucite and the c -axis direction of chrysotile may be sufficiently close for the brucite to replace the chrysotile most readily along that direction. Poitevin and Graham¹ have likewise reported this replacement in the Thetford region.

The specimen shown in Plate I fig. 2, consists of an asbestos vein one segment of which has been replaced by brucite, which retains the fibrous character of the original material. The sketch, fig. 3, shows the relation of the minerals in the specimen. On each side of the brucite a thin layer of magnetite, within the brucite, lies adjacent to an equally thin band of serpentine, somewhat discontinuous. The two outer portions of the specimen are asbestos. It is to be noted that the directions of the fibres in the asbestos portions are parallel, whereas the fibre direction in the brucite is inclined to the former. The specimen has apparently suffered distortion after forming, with the brucite as the incompetent layer.

The brucite portion is made up of platy crystals with a tendency towards a fibrous character, as is clearly seen in the photograph. The plates are, in general, normal to the wall of the vein and not parallel to each other. The regularity of the orientation has been somewhat obscured by the distortion of the brucite band. Like the fibrous nemalite first described the platy brucite has the c -axis of all the individuals lying in a plane across the fibre length. The platy

¹ Poitevin, Eugene and Graham, R. P. D., Contributions to the Mineralogy of Black Lake Area, Quebec: *Mus. Bull. No. 27, Geol. Series, No. 35, Can. Dept. Mines; Geol. Surv.*, Feb. 1918, p. 22.

material however does not have a common direction for the a -axis, as is true in the nemalite.

Mr. C. D. West of the Mallinckrodt Chemical Laboratory at Harvard has dehydrated the Quebec nemalite and has made an x -ray study of the resulting product. His note follows:

STRUCTURE OF THE DEHYDRATED PSEUDOMORPH OF BRUCITE
AFTER CHRYSOTILE

C. D. WEST

A specimen of fibrous brucite was provided by Mr. Berman with the information that the brucite a -axis lay in the fibre axis. This was confirmed. On examination with a homogeneous x -ray beam perpendicular to the fibre axis the dehydrated product showed a perfect orientation of the MgO , with the $[110]$ direction in the fibre axis. This orientation was retained even after heating in an oxygen-gas flame. The identity periods of the three substances chrysotile, brucite and dehydrated brucite (periclase) along the fibre axis are, using accepted values of the constants, 5.33, 3.13, and 2.98\AA . A few weak extra reflections were observed on some of the photographs between the zero and the first layer lines of MgO . I plan to study this process further.

J. Bohm (*Zeit. Krist.*, **68**, 567, 1928) has described a similar effect on dehydrating single crystals of goethite and diascore, the hexagonal form Fe_2O_3 being completely oriented with respect to the previous rhombic axes of FeO_2H . From my own observations it seems clear that the products of the decomposition of single crystals of $\text{Ca}(\text{OH})_2$, brucite, and calcite preserve a certain degree of orientation, although it is not nearly so marked as in the cases mentioned. A remark of Bohm's shows that, as far as calcite is concerned, this effect had previously escaped notice.

CALAVERITE AND THE LAW OF COMPLICATION

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Few crystallographers would venture to think that the Law of Simple Rational Intercepts and Indices is not a perfectly general truth; yet this is the conclusion reached by Victor Goldschmidt (Heidelberg), Charles Palache and the present writer¹ in a recently published account of an extended study of calaverite, the crystallized di-telluride of gold which has puzzled crystallographers since the end of the last century. Tersely written in German, assuming familiarity with the Goldschmidt method of crystal measurement and discussion, and making use of a new and significant crystallographic conception, this joint account may have presented some difficulties to the English-speaking reader. Encouraged by Professor Palache, the junior author has therefore prepared the present paper which gives the essential theory used in the joint paper and its application to the crystallography of calaverite, followed by a formal statement of the crystallography of this remarkable mineral. The opportunity is also taken to give a brief account and discussion of Professor Goldschmidt's application of the Law of Complication to fields outside of crystallography.

THE CLASSICAL LAWS OF CRYSTALLOGRAPHY

The goniometric study of crystals has led to three empirical generalizations which have long been accepted as the laws of systematic crystallography.

1. The Law of Constancy of Angles.
2. The Law of Zones.
3. The Law of Rationality.

The Law of Constancy of Angles states that the angular relations of the forms of crystals of any species are constant and proper to the species.

The Law of Zones states that crystal faces occur in groups in each of which the faces are parallel to a common axis.

By the Law of Rationality, the Law of Simple Rational Intercepts and Indices is generally understood. This law may be stated as follows: With suitably chosen axes and axial lengths, every face of a crystal is parallel to a plane which cuts one axis at the unit

¹ Ueber Calaverit, *N. J. f. Min.*, Beil. Bd. 63A, pp. 1-58, figs. 1-22, pls. i-x, 1931.

length and cuts the other axes either at infinity or at distances from the axial centre which are simple rational multiples or fractions of the corresponding unit lengths; and therefore the angular relations of every face may be given, with reference to suitable crystal axes, by symbols involving, on any system of notation, only simple rational numbers, zero and infinity.

These laws determine the procedure of crystallographic investigation. A number of crystals of a species are measured, and it is observed that like forms on all the crystals have the same angular relations. The measurements are projected and the faces are found to lie in zones. Suitable axes are chosen and the appropriate simple rational symbols are given to all the observed plane faces. The consistent success of this procedure has consolidated the classical laws of crystallography and placed them in a position of apparently unassailable security.

The study of calaverite was naturally approached in this way; but repeated investigations² of excellent material showed that, while the first and second laws held strictly true, the third failed. It is not possible to choose axes for calaverite so that the majority of the forms receive simple symbols; and no admissible assumptions of twinned or heterogeneous structure will serve to bring this crystal species within the Law of Rationality in its generally accepted form. No one seriously thought that the Law of Rationality might be inadequate, and thus the tiny, brilliant, golden crystals of calaverite remained complete enigmas.

GOLDSCHMIDT'S LAW OF CRYSTALLOGRAPHY— THE LAW OF COMPLICATION

In the gnomonic projection, which forms the graphical foundation of Professor Goldschmidt's system, the Law of Constancy of Angles is proved by the constancy of the co-ordinates of like nodes (projection points of face normals) in crystals of the same species. The Law of Zones is apparent in the fact that the nodes of any one crystal lie on a network of straight lines extending to infinity. And

² Of these only two were published: S. L. Penfield and W. E. Ford, *Amer. Jour. Sci.*, **xii**, pp. 225–246, 1901; G. F. H. Smith, *Min. Mag.*, **xiii**, pp. 122–150, 1902. Laborious unpublished studies by Palache, Goldschmidt, Moses, Goldschmidt and Görgy, Goldschmidt and Neff, and Palache and Peacock, representing efforts spread over more than thirty years, confirmed and extended the previous observations, but failed to reconcile them with the accepted laws of crystallography.

the Law of Rationality appears in the fact that the linear distances between the nodes in a zone are simple rational fractions or multiples of a suitably chosen unit length, when the plane of the projection is normal to a zone axis.

In any zone certain nodes, usually those corresponding to the largest and most frequent faces, may be recognized as principal nodes. In zones having one such node at infinity (∞), another being taken as the origin of measurement (0), and a third important node being taken to give the unit of spacing (1), it is found by statistical study³ that the remaining nodes of the zone segment between the nodes (0) and (∞) occur most frequently at distances $\frac{1}{2}$, 2, less frequently at $\frac{1}{3}$, $\frac{2}{3}$, $\frac{3}{2}$, 3, and rarely at other distances from the end-node (0) (fig. 1). Thus, out of the great variety of simple rational spacings which might occur in a zone, there are ev-

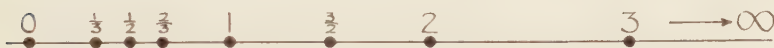


FIG. 1. Gnomonic projection of a normal zone having one principal node at infinity. Between the end-nodes 1, ∞ , the derived nodes are spaced according to the terms of the normal complication series N_3 .

idently certain preferred arrangements which Goldschmidt has recognized as normal series, N_0 , N_1 , N_2 , N_3 , . . .

$N_0: p=0$								∞
$N_1: p=0$					1			∞
$N_2: p=0$			$\frac{1}{2}$		1		2	∞
$N_3: p=0$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$		1	$\frac{3}{2}$	2	3
								∞

Except in the series N_0 , in which there is no development between the end-nodes, 0, ∞ , the series show a numerical symmetry about the node 1, which is named the dominant,⁴ the terms on the one side being the reciprocals of those on the other. From any series N_n the terms of the next higher series N_{n+1} , are obtained by adding 1 to each term of the series N_n , giving the terms $1 \cdots \infty$ of the series N_{n+1} , and then writing the reciprocals of the terms

³ V. Goldschmidt, Ueber Entwicklung der Krystallformen: *Z. f. Kryst.*, xxviii, pp. 1-35, 414-451, 1896-97. This account is based on these two papers and on conversations with Professor Goldschmidt. The statistical study referred to appears on p. 10.

⁴ In the diatonic series, the term 1 corresponds with the dominant of the scale (see below, p. 330).

thus obtained to give the terms $1 \cdots 0$ of the series N_{n+1} . The number of series may be extended indefinitely, but series higher than N_3 are infrequent in crystal zones.

In the belief that these preferred crystallographic number series are of fundamental significance, Professor Goldschmidt has framed a theory of crystal structure and zonal development which leads naturally to the observed preferred arrangements of crystal faces in a zone. This theory rests on two hypotheses:

1. A crystal is a rigid system of like and similarly oriented particles.
2. Every crystal face is a plane normal to a force of attraction exerted from the centre of the crystal particle.

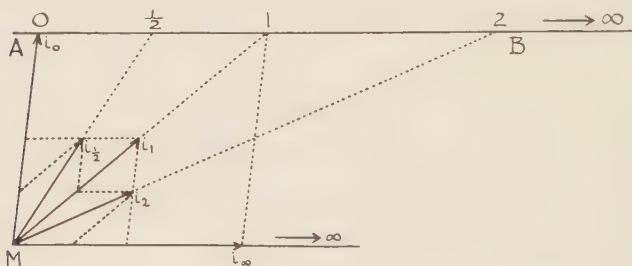


FIG. 2. Section in the plane of a normal zone showing the development of derived forces (and therefore faces) by complication between the principal forces (or faces) i_0 , i_∞ .

The construction in fig. 2 is a section in the zone-plane of a zone with principal (end) nodes 0 , ∞ . AB is the trace of the gnomonic plane and M is the crystal centre. Since 0 and ∞ are principal nodes of the zone, i_0 , i_∞ are the principal attraction forces, according to hypothesis 2. The forces i_0 , i_∞ are fixed in direction by the nodes 0 , ∞ , but their intensities, given by the lengths of the arrows from M , are arbitrary. If the entire forces i_0 , i_∞ or aliquot parts, of them, combine to give a resultant by the parallelogram of forces, a new force is produced giving the dominant node 1 and therefore also the corresponding face. Since the principal forces would be exhausted if they combined completely to give a resultant, Goldschmidt assumes that the principal forces divide into aliquot parts, normally in halves, one half of each principal force continuing to act in its respective principal direction and the remaining halves combining to give the resultant force.

$\frac{1}{2}i_0 + \frac{1}{2}i_\infty = i_1$, by the parallelogram of forces, and therefore, from the initial series:

$$N_0: p=0 \infty$$

we obtain the next higher series:

$$N_1: p=0 \ 1 \ \infty$$

By combining one half of the remainder of i_0 with one half of i_1 , a resultant $i_{\frac{1}{2}}$ is obtained; and similarly one half of i_1 with one half of the remainder of i_∞ gives i_2 .

$$\frac{1}{4}i_0 + \frac{1}{2}i_1 = i_{\frac{1}{2}}; \quad \frac{1}{2}i_1 + \frac{1}{4}i_\infty = i_2$$

Whence we obtain the next higher series:

$$N_2: p=0 \ \frac{1}{2} \ 1 \ 2 \ \infty$$

Similarly, the successive combination of halves of the remainders of the principal forces with halves of the newly formed resultants give further resultants corresponding to the new terms of the higher series.

To this process of division and combination of parts Professor Goldschmidt has given the name *Complication*, a process which he believes to be fundamental, not only in crystallography, but also in other widely dissimilar fields. In the realm of crystallography complication means specifically the division of the principal crystal forces (giving the principal faces of a zone) into halves, the combination of these parts to give a resultant force (derived face), and the repeated formation of new resultants between adjacent forces by halving and combination of halves.

The empirically found series:

$N_0: p=0$								∞
$N_1: p=0$				1				∞
$N_2: p=0$		$\frac{1}{2}$		1		2		∞
$N_3: p=0$	$\frac{1}{8}$	$\frac{1}{2}$	$\frac{2}{3}$	1	$\frac{3}{2}$	2	3	∞

thus becomes the *normal complication series*.

In many zone segments neither of the principal nodes is at infinity. The number series in such zone segments are not normal complication series. If $p_1 \cdots p \cdots p_2$ be such a series, it must be transformed into the standard form $0 \cdots \infty$ by writing $(p-p_1)/(p_2-p)^5$ for each term of the series. This transformation of series into the standard form plays an important part in the critical

⁵ For the proof of this formula and the justification for the transformation, see V. Goldschmidt, *Zeit. f. Kryst.*, xxviii, pp. 22-23, 1896-97.

discussion of the number series in crystallography and in other fields.

The complication series and the transformation formula for transforming any number series into the standard form $0 \cdots \infty$, give a valuable criterion for the critical discussion of crystal form systems. Uncertain forms may be retained or rejected according to whether they are likely terms of the complication series or not; and well substantiated forms with unusual complication numbers afford evidence of disturbance in the free development of zones.⁶

We are now in a position to state and understand Goldschmidt's general law of crystallography, which may be briefly expressed as follows:

The form system of a crystal results from complication between the principal forces of the crystal particles.

From what has already been given, it is clear that this law accepts and includes, by implication, the Law of Constancy of Angles and the Law of Zones, and recognizes the principal of rationality in the progressive halving of forces which is inherent in the process of normal complication. Goldschmidt's law is more general, however, as we shall see later; at the same time it is more specific in that it recognizes preferred rational number series where-as any simple rational number series would satisfy the older law.

THE LAW OF COMPLICATION APPLIED TO CALAVERITE

According to the principles developed above, the goniometric investigation of a crystal by the Goldschmidt method involves finding the principal nodes and discussing the complication in each zone. The principal nodes are given the simplest possible symbols by suitable choice of axes and unit form, and thus the best elements of the crystal are determined. Then the remaining nodes, which are derived from the principal nodes by complication, are given rational symbols determined by their spacing with respect to the principal nodes. The practical result is the same as that reached by the older method, except that the choice of elements rests on a securer basis since it is made to give the lowest complication between the principal nodes. The theoretical result of the investigation, however, is to prove the validity of the Law of Complication

⁶ Outside of Professor Goldschmidt's laboratory, this method of critical discussion of form systems has been usefully applied by W. T. Schaller, *The Mercury Minerals from Terlingua, Texas. U. S. Geol. Sur., Bull.*, **405**, 1909.

as the principal governing the systematic arrangement of crystal faces.

Since the principal nodes could always be regarded as the simplest forms of the crystal, it was natural that the very first step in the Goldschmidt discussion of a projection was to find axes to which the principal nodes were related in a simple manner. But for calaverite this could not be done, and therefore the Goldschmidt method of approach failed, like the others, in the earlier investigations of this mineral. During the last attempt to solve the calaverite puzzle, which at first seemed as hopeless as ever, it occurred to Professor Goldschmidt that it might be better to disregard the question of symbols at first, and to proceed rigorously by finding the principal nodes and discussing the complication between them. This met with immediate success. The entire form system of ninety-two confirmed forms was found to be developed by complication from a few principal nodes; and thus remarkable confirmation of the Law of Complication was obtained in a case where the Law of Simple Rational Intercepts and Indices had failed.

With the best choice of axes, all the principal nodes, except one pair, received the customary simple symbols; the exceptional pair received the exceedingly complicated symbol ($\bar{3}.5.29$), with only tolerable agreement between the calculated and observed angles. It thus became evident that principal nodes might sometimes be forms with complicated, if not quite irrational symbols. Such principal nodes Professor Goldschmidt has proposed to name *singular nodes*.⁷ The singular node pair C was the key to the calaverite puzzle. When it was recognised that the node C with its complicated symbol was yet the simplest node, namely the node of origin (0), in each zone containing C, and that every zone of calaverite gave a more or less complete N_3 complication series without extra terms, it was apparent that calaverite conformed strictly to the Law of Complication as it was formulated many years ago.

THE SYSTEMATIC CRYSTALLOGRAPHY OF CALAVERITE

The practical problem of formally presenting the crystallography of calaverite still remains. The complicated relations are best shown graphically, but for formal purposes they must be expressed quantitatively.

⁷ This Journal, **xvi**, p. 78, 1931.

Calaverite is monoclinic and isomorphous with sylvanite. The orthodome zone is developed prismatically; the measurements are therefore projected and discussed in M_2 position (projection plane

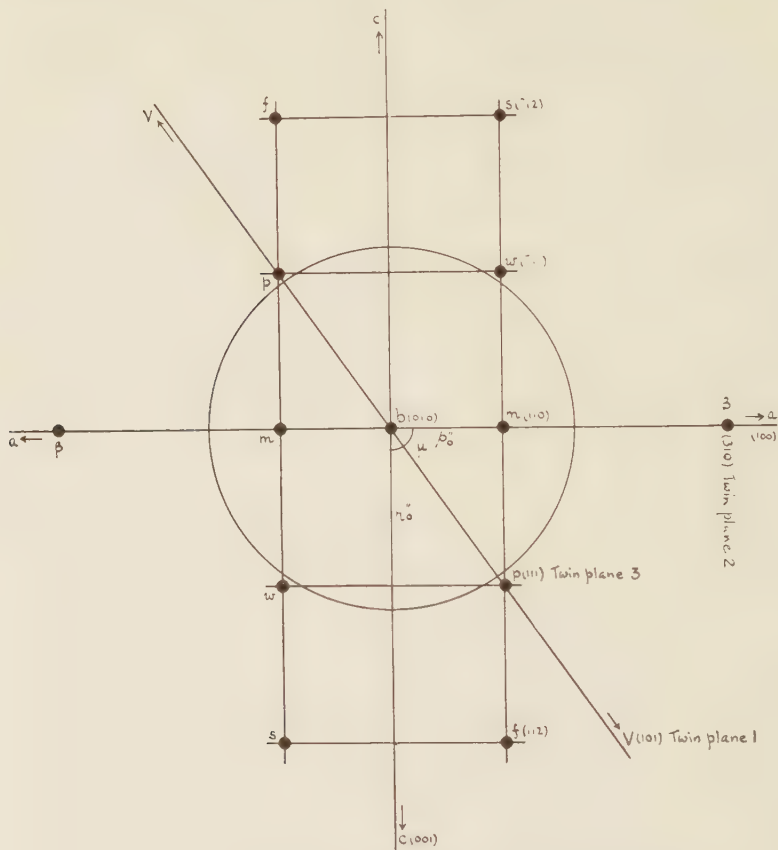


FIG. 3. Calaverite. Gnomonic projection of the S-forms and graphical elements, showing also the three known twinning planes.

normal to the symmetry axis). In this position (fig. 3) the Goldschmidt projection elements are:

$$r_0'' = 0.8702; p_0'' = 0.6136; q_0'' = 1; \mu = 89^\circ 52'(M_2).$$

The corresponding polar elements in M_1 position (normal position, projection plane parallel to the symmetry axis) are:

$$p_0 = 0.7051; q_0 = 1.1492; r_0 = 1; \mu = 89^\circ 52'(M_1).$$

These elements are equivalent to the linear elements:

$$a:b:c=1.6298:1:1.1492; \beta=90^\circ 08'.$$

These are the fundamental elements of calaverite; from the isomorphism with sylvanite we have named them the *S*-elements, and the 10 known forms of calaverite which are simply related to these elements we have named the *S*-forms.

CALAVERITE—MONOCLINIC
S-ELEMENTS AND FORMS

$r_0''=0.8702; \quad p_0''=0.6136; \quad q_0''=1; \quad \mu=89^\circ 52' (M_2)$ or $p_0=0.7051; \quad q_0=1.1492; \quad r_0=1; \quad \mu=89^\circ 52' (M_1)$ or $a:b:c=1.6298:1:1.1492; \quad \beta=90^\circ 08'$				
$c(001)$	$a(100)$	$\beta(310)$	$p(111)$	$f(112)$
$b(010)$	$m(110)$	$V(101)$	$w(\bar{1}11)$	$s(\bar{1}12)$

TWINNING LAWS

1. The twinning and composition plane is $V(101)$; the axes of the prismatically developed zones of the two individuals are parallel.

2. The twinning and composition plane is $\beta(310)$; the axes of the prismatically developed zones of the two individuals intersect at $122^\circ 58'$.

3. The twinning and composition plane is $p(111)$; the axes of the prismatically developed zones of the two individuals intersect at $93^\circ 40'$.

Thus far the statement of the crystallography of calaverite is perfectly normal; but we have accounted for only 10 of the 92 known forms. On the *S*-elements (M_1) the singular nodes *C* have the exceedingly complicated symbol $\bar{5}.29.3$, and thus it is clear that, since these are the strongest nodes of the form system, all the forms of calaverite, except the 10 simple *S*-forms, will receive symbols of great complexity on the *S*-elements. A table of such symbols would be useless for practical purposes and at variance with the theoretical part of our study.

The only alternative, and it is admittedly a makeshift, is to refer the forms of calaverite to several closely related groups of elements of triclinic character; in this way the great majority of the forms receive simple symbols closely related to their simple complication numbers.

Fig. 4 shows a part of the zone-net of calaverite corresponding to the *S*-elements (dotted), and in full lines sufficient construction

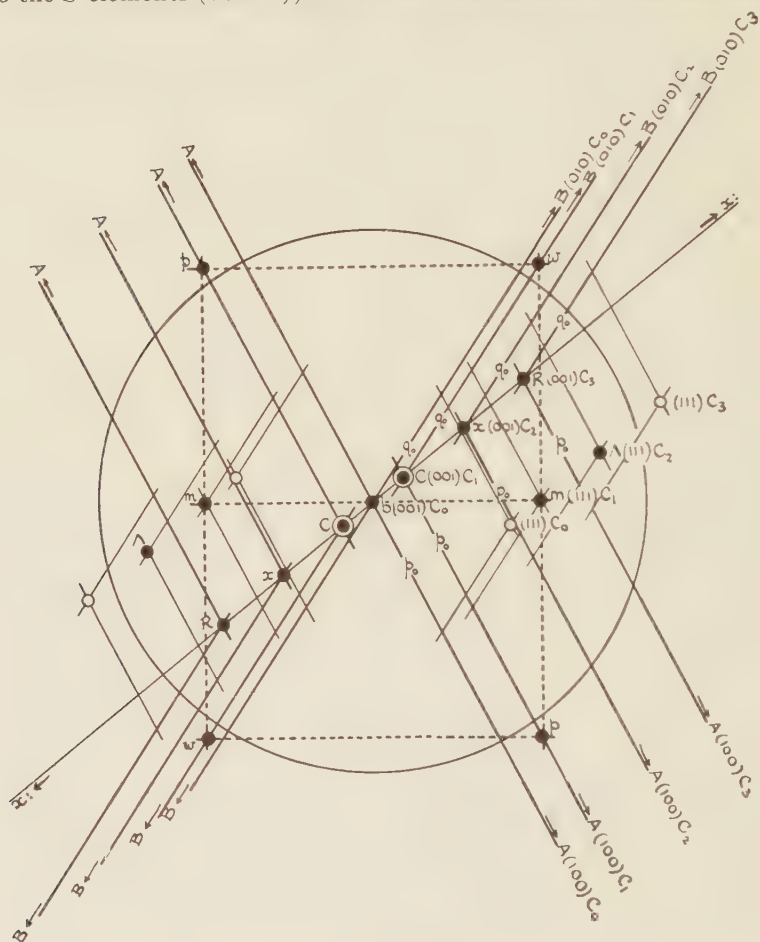


FIG. 4. Calaverite. Gnomonic projection of the C_1 , C_2 , C_3 , C_0 graphical elements (polar axis and unit forms). The principal *S*-zones are given in broken lines. The blank points are forms not known; the double circles are the singular nodes *C*. *x*: is one of the incongruous CC_2 -forms lying in zone with $C(001)C_1$ and a node of the C_2 -net.

to illustrate the groups of elements (the calaverite- or *C*-elements) which serve to accommodate most of the forms of calaverite with simple symbols.

C_1 -elements: Polar axes ABC ; resp. proj. elements $p_0 q_0 r_0 = 1$

C_2 -elements: Polar axes ABx ; resp. proj. elements $p_0 q_0 r_0 = 1$

C_3 -elements: Polar axes ABR ; resp. proj. elements $p_0 q_0 r_0 = 1$

C_0 -elements: Polar axes ABb ; resp. proj. elements $p_0 q_0 r_0 = 1$

These groups of elements have the same polar axes in the plane of the projection, namely AB , and the same projection elements $p_0 q_0 r_0$. The remaining polar axes lie in a zone.

It is of no value to express these groups of elements as triclinic linear elements. The linear constants do not show the close relations which exist between the several groups of polar elements, and they would imply a triclinic interpretation of calaverite which we reject.

If calaverite is measured again, it will be in all probability with the 2-circle goniometer. The most useful practical constants to correlate with future work are therefore the 2-circle angles of the polar axes (or primitive pinacoids) ABC , etc., and the projection elements in the plane of the projection, $p_0 q_0 r_0$.

Another reason for not recasting the elements in orthodox triclinic form is the fact that we know that even these four sets of axes, or seven sets, when we include the repetition of three of them by the symmetry axis b , are insufficient to account for all the forms. There remain a number of prismatic forms (CC_2 -forms) which lie in zone with the base $C(001)$ of the C_1 -elements and with nodes of the incongruous C_2 -elements. These forms are therefore incongruous to both groups of elements and cannot be given simple symbols.

The following tabulation⁸ is therefore offered as the simplest practical quantitative expression of the remarkable form system of calaverite. It will be observed that all the S -forms appear also in the tables of C -forms.⁹

To the reader who may be tempted to measure calaverite on the two-circle goniometer, the following may be useful. Adjust the prismatically developed zone; the face b then lies in the pole and at the centre of the projection. Find the form $m(111) C_1$, appearing as a pair of excellent faces with polar distance (ρ) $31^\circ 32'$ and with azimuths (ϕ) differing by 180° . With the azimuth

⁸ In principle, this mode of presentation is the same as that adopted by G. F. H. Smith, *Min. Mag.*, xiii, p. 125, 1902.

⁹ In the joint publication, *N. J. f. Min.*, Beil. Bd. 63A, 1931, will be found the corresponding measured and calculated two-circle angles, tables 6-10, pp. 30-34.

CALAVERITE

C₁-GRAPHICAL ELEMENTS AND FORMS

$A(100)$	$\phi=62^{\circ} 11'$	$\rho=90^{\circ} 00'$	$p_0=0.5419$	
$B(010)$	$\phi=57^{\circ} 20'$	$\rho=90^{\circ} 00'$	$q_0=0.4646$	
$C(001)$	$\phi=38^{\circ} 42'$	$\rho=8^{\circ} 02'$	$r_0=1$	
$C(001)$	$n(302)$	$w(021)$	$\sigma(131)$	$d(211)$
$B(010)$	$p(201)$	$\xi(031)$	$v(1\bar{1}1)$	$\phi(221)$
$A(100)$	$i(301)$	$r(0\bar{1}1)$	$G(1\bar{2}1)$	$\gamma(231)$
$E(110)$	$L(\bar{1}03)$	$W(0\bar{2}1)$	$\kappa(1\bar{3}1)$	$g(2\bar{1}1)$
$c(1\bar{1}0)$	$Q(\bar{1}02)$	$\Xi(0\bar{3}1)$	$M(\bar{1}11)$	$D(2\bar{1}1)$
$V(610)$	$y(\bar{1}01)$	$\tau(122)$	$s(131)$	$\Phi(221)$
$l(103)$	$P(201)$	$\iota(\bar{1}22)$	$t(\bar{1}\bar{1}1)$	$\Gamma(2\bar{3}1)$
$q(102)$	$I(\bar{3}01)$	$m(111)$	$\Theta(1\bar{2}1)$	$\alpha(321)$
$o(101)$	$u(011)$	$\theta(121)$	$\Sigma(1\bar{3}1)$	$\chi(331)$
				$f(3\bar{1}1)$

C₂-GRAPHICAL ELEMENTS AND FORMS

$A(100)$	$\phi=62^{\circ} 11'$	$\rho=90^{\circ} 00'$	$p_0=0.5419$	
$B(010)$	$\phi=57^{\circ} 20'$	$\rho=90^{\circ} 00'$	$q_0=0.4646$	
$x(001)$	$\phi=38^{\circ} 42'$	$\rho=23^{\circ} 04'$	$r_0=1$	
$x(001)$	$e(101)$	$\psi(0\bar{1}1)$	$\lambda(\bar{1}\bar{1}1)$	$\delta(2\bar{1}1)$
$B(010)$	$\omega(201)$	$k(0\bar{2}1)$	$z(\bar{1}21)$	$H(221)$
$A(100)$	$X(\bar{1}01)$	$\Lambda(111)$	$\Delta(211)$	$h(321)$
$E(110)$	$\Omega(201)$	$Z(121)$	$\rho(221)$	$\beta(331)$
$c(1\bar{1}0)$	$\Psi(011)$	$\Pi(1\bar{1}1)$	$j(2\bar{1}1)$	$F(3\bar{1}1)$
$V(610)$	$K(021)$	$O(1\bar{2}1)$	$U(2\bar{2}1)$	

C₃-GRAPHICAL ELEMENTS AND FORMS

$A(100)$	$\phi=62^{\circ} 11'$	$\rho=90^{\circ} 00'$	$p_0=0.5419$	
$B(010)$	$\phi=57^{\circ} 20'$	$\rho=90^{\circ} 00'$	$q_0=0.4646$	
$R(001)$	$\phi=38^{\circ} 42'$	$\rho=35^{\circ} 38'$	$r_0=1$	
$R(001)$	$E(110)$	$S(101)$	$v(\bar{1}21)$	$N(2\bar{1}\bar{1})$
$B(010)$	$c(1\bar{1}0)$	$\pi(201)$	$T(211)$	$\epsilon(221)$
$A(100)$	$V(610)$	$\eta(0\bar{1}1)$	$\nu(221)$	

C_0 -GRAPHICAL ELEMENTS AND FORMS

$A(100)$	$\phi = 62^\circ 11'$	$\rho = 90^\circ 00'$	$p_0 = 0.5419$
$B(010)$	$\phi = 57^\circ 20'$	$\rho = 90^\circ 00'$	$q_0 = 0.4646$
$b(001)$	$\phi = -$	$\rho = 0$	$r_0 = 1$

$b(001)$	$A(100)$	$c(1\bar{1}0)$	$J(102)$	$\mu(112)$
$B(010)$	$E(110)$	$V(610)$	$Y(0\bar{2}1)$	$\xi(212)$

 CC_2 -FORMS

a :	Prismatic form in zone with $C(001)C_1$ and $\rho(221)C_2$
e :	$e(101)C_2$
ω :	$\omega(201)C_2$
π :	$\pi(1\bar{1}1)C_2$
ε :	$\varepsilon(\bar{1}21)C_2$
K :	$K(021)C_2$
x :	$x(001)C_2$
Λ :	$\Lambda(111)C_2$

of m as zero meridian the remaining forms will fall into the nets given by the above graphical elements or into the same nets repeated by the symmetry axis b (fig. 4). This agreement will be obtained only if the measured termination is of the same hand as that which we have chosen. If the termination is left handed with respect to our right handed termination (and right and left handed terminations are equally frequent), the measurements will correspond to nets in mirror image relation to fig. 4 (obtained by plotting azimuths in the negative sense). If the termination is a twin after the first law (prismatic axes in common), the observed forms will fall on fourteen nets, the seven shown in fig. 4 and the seven obtained by constructing a similar figure with negative azimuths.

THE LAW OF COMPLICATION IN OTHER FIELDS

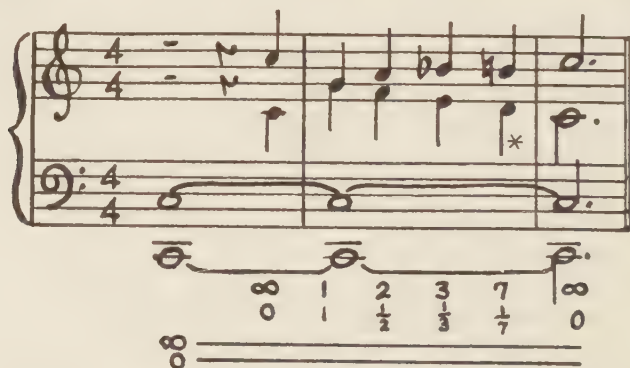
In music. More than thirty years ago Professor Goldschmidt showed some striking similarities between the normal crystallographic number series and the series of numbers obtained by suitably transforming the relative vibration periods of the notes of the diatonic scale.¹⁰

¹⁰ *Ueber Harmonie und Complication*, Berlin, 1901.

The relative vibration periods (z) of the notes of a major scale, C D E F G A B C', are very close to the numbers, $1 \frac{9}{8} \frac{5}{4} \frac{4}{3} \frac{3}{2} \frac{5}{3} \frac{15}{8} 2$, respectively. Transforming this series into the form $0 \cdots \infty$, a series of numbers (p) similar to a normal complication series is obtained.

	I	II	III	IV	V	VI	vii	VII	VIII
	C	D	E	F	G	A	(B ^b)	B	C'
$z =$	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	($\frac{7}{4}$)	$\frac{15}{8}$	2
$p = \frac{z-1}{2-z} =$	0	$\frac{1}{7}$	$\frac{1}{3}$	$\frac{1}{2}$	1	2	(3)	7	∞

Like a normal complication series, this series is symmetrical about the term 1, which corresponds with the fifth or dominant of the diatonic scale. The term (3), corresponding to (B^b), is not in the scale of C major, but is closely related to it musically. Notes with complication numbers of equal rank give pleasing combinations; and the passage obtained by combining notes of equal rank in order of increasing complication, over a sustained bass given by the end terms of the series, is musically perfectly satisfactory.



The terms $\frac{1}{7}$, 7, are not found in normal crystal series. In the diatonic series the corresponding notes, D, B, make harsh discords against the end terms, C, C'; but at* in the above passage the effect

is inoffensive due to the wide intervals between the discordant notes.

On this foundation Professor Goldschmidt has built up an elaborate system of harmonic analysis.

In colour. The most prominent of the Fraunhofer lines of the solar spectrum, *A* (purple), *B* (scarlet), *C* (red), *D* (yellow), *E* (green), *F* (blue), *G* (indigo), *H* (violet), have the measured wave-lengths (λ) in the following table. The lines cover approximately an octave of the spectrum. Their relative wave-lengths are given very closely by the rational number series, $2 \cdots 1$, and their relative periods (z) by the series $1 \cdots 2$. Transforming this series into the form $0 \cdots \infty$, the series of numbers obtained (p) is again essentially a complication series.

FRAUENHOFER LINE	A	B	C	D	E	F	G	H
λ	7608	6870	6563	5893	5270	4861	4308	3969 $\mu\mu$
proportional to.....	1.935	1.748	1.670	1.500	1.341	1.237	1.096	1.010
or nearly.....	2.000	1.750	1.667	1.500	1.333	1.250	1.111	1.000
or.....	2	$\frac{7}{4}$	$\frac{5}{3}$	$\frac{3}{2}$	$\frac{4}{3}$	$\frac{5}{4}$	$\frac{10}{9}$	1
$z = 2/\lambda$	1	$\frac{8}{7}$	$\frac{6}{5}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{8}{5}$	$\frac{9}{8}$	2
$p = 2(z-1)/(2-z)$	0	$\frac{1}{8}$	$\frac{1}{2}$	1	2	3	(8)	∞

The series (p) is remarkably like the normal complication series N_3 ; the term (8) is additional and it corresponds to the colour indigo, which is a colour difficult to distinguish. Except for this term the series is symmetrical about the term 1, which corresponds to yellow, the dominant (brightest) colour in the spectrum. On this basis Professor Goldschmidt develops an extended analogy between sound and colour, and a method for analysing colour combinations.¹¹

In cosmic space. The distances of the planets and the asteroids from the sun, reduced so as to make the distance of the earth equal to 10, have long been known to correspond approximately to a number series due to Titius and advocated by Bode.¹² This number series is obtained by writing the series 0, 1, 2, 4, 8, 16, 32, 64, 128, multiplying each term by 3 and adding 4 to each product. The

¹¹ *Ueber Harmonie und Complication*, p. 83 et seq.

¹² H. Shapley and H. E. Howarth, *A Source Book in Astronomy*, New York, 1929, p. 180.

numbers thus obtained (t) compare with the proportionate mean measured distances (d) as follows:

	MER.	VEN.	EARTH	MARS	AST.	JUP.	SAT.	URAN.	NEP.
d	3.87	7.23	10.00	15.24	—	52.03	95.39	191.82	300.55
t	4	7	10	16	28	52	100	196	388

Due to the serious discrepancy in the case of Neptune, and the fact that the first term is arbitrary and should really be ($\frac{1}{2} \times 3 + 4$) = $5\frac{1}{2}$, this number law is now generally regarded as a curiosity without rational explanation.¹³

In a long paper on Harmony in Cosmic Space Professor Goldschmidt¹⁴ has shown that the relative mean distances of the planets from the sun, transformed, when necessary, by the general method already used in the discussion of crystallographic, diatonic and spectral series, conform to the Law of Complication.

In the following table D is the measured distance of each planet from the sun, in millions of kilometers.

	MER- CURY	VENUS	EARTH	MARS	JUPITER	SATURN	URANUS	NEP- TUNE
D	57.5	107.5	148.7	226.5	773.2	1417.8	2851.3	4467.5
$d = D/733$	0.078	0.147	0.203	0.309	1.055	1.935	3.891	6.096
or nearly . .	0.077	0.143	0.200	0.333	1.000	2.000	4.000	6.000
or	$\frac{1}{13}$	$\frac{1}{7}$	$\frac{1}{5}$	$\frac{1}{3}$	1	2	4	6

The mean distances are thus very closely represented by the series of rational numbers in the last line of the above table.

The major planets, together with the sun and outer space as end terms, give an incomplete complication series:¹⁵

	SUN	JUPITER	SATURN	URANUS	NEPTUNE	OUTER SPACE
d	0	1	2	4	6	∞
$p = d/2$	0	$\frac{1}{2}$	1	2	3	∞

¹³ J. Jeans, *The Universe Around Us*, Cambridge, 1929, p. 20.

¹⁴ V. Goldschmidt, Ueber Harmonie im Weltraum: *Ann. d. Naturphil.* (Ostwald), v, pp. 51-110, 1905.

¹⁵ See Appendix.

Similarly the minor planets, with the sun and Jupiter as end terms, give terms of the complication series:

	SUN	MERCURY	VENUS	EARTH	MARS	JUPITER
d	0	$1/13$	$1/7$	$1/5$	$1/3$	1
$p = d/(1-d)$	0	$1/12$	$1/6$	$1/4$	$1/2$	∞
$p' = 4p$	0	$1/3$	$2/3$	1	2	∞
$p'' = 6p$	0	$1/2$	1	$3/2$	3	∞

Again, the number series corresponding to the distances of the larger satellites of Jupiter and of Uranus from their respective parent bodies, give incomplete complication series, even without transformation:

	JUPITER	JO	EUROPA	GANYMEDE	CALLISTO	OUTER SPACE
D	0	419	666	1064	1871	∞
$d = D/970$	0	0.44	0.70	1.11	1.95	∞
p	0	$1/2$	$2/3$	1	2	∞

	URANUS	ARIEL	UMBRIEL	TITANIA	OSBERON	OUTER SPACE
D	0	205	285	443	583	∞
$d = D/417$	0	0.49	0.68	1.06	1.40	∞
p	0	$1/2$	$2/3$	1	$3/2$	∞

D is the measured mean distance of each satellite in thousands of kilometers.

And in like manner the satellites of Saturn form complication series,¹⁶ and the 700 odd known asteroids are shown to fall into groups concentrated at distances from the sun corresponding to terms of the complication series.¹⁷

From these facts Professor Goldschmidt develops a cosmogonic theory in which one of the leading thoughts is that groups of bodies forming complication series (or cosmic chords) were each generated in distinct epochs.

¹⁶ V. Goldschmidt, Ueber Harmonie im Weltraum: *Ann. d. Naturphil.* (Ostwald), **v**, p. 77, 1905.

¹⁷ V. Goldschmidt, Harmonie im Reich der Planetoiden: *Ann. d. Naturphil.* (Ostwald), **ix**, pp. 383-392, 1912.

THE SIGNIFICANCE OF THE LAW OF COMPLICATION

In the following table we have re-assembled some of the number series found in crystallography, musical harmony, colour and cosmic space. The similarity of the several series is indeed impressive. The examples given, which are the fundamental ones, contain no terms not found in the normal complication series III; the third order of complication seems to be a natural limit which is overstepped only rarely either in crystallography or in the other realms. The collected series show the same order of frequency of terms as that found in the crystallographic series: 0, ∞ (12 times); 1 (10 times); $\frac{1}{2}$, 2 (7 to 8 times); $\frac{1}{3}$, 3, $\frac{2}{3}$, $\frac{3}{2}$ (2 to 6 times). In each case the numbers represent lengths or their reciprocals, and where transformation has been necessary to bring the series into the standard form $0 \cdots \infty$, it has been done by a standard operation whose significance in crystallography is understood, implying a change in the position of the projection plane.

COMPLICATION SERIES

Crystallography

Normal complication series I.....	$p=0$	•	•	•	1	•	•	•	∞
Normal complication series II.....	$p=0$	•	$\frac{1}{2}$	•	1	•	2	•	∞
Normal complication series III.....	$p=0$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	1	$\frac{3}{2}$	2	3	∞

Music

Major common chord (root position) ¹⁸	$p=0$	$\frac{1}{3}$	•	•	1	•	•	•	∞
Major common chord (second inversion).....	$p=0$	•	$\frac{1}{2}$	•	•	•	2	•	∞
Minor common chord (first inversion).....	$p=0$	$\frac{1}{3}$	•	•	•	•	2	•	∞
Chord of the dominant seventh.....	$p=0$	$\frac{1}{3}$	•	•	1	•	•	3	∞

Colour

Purple, scarlet, red, yellow, green, blue, violet..	$p=0$	$\frac{1}{3}$	$\frac{1}{2}$	•	1	•	2	3	∞
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Cosmic Space

Major planets: Sun, Jupiter, Saturn, Uranus, Neptune, Outer Space.....	$p=0$	•	$\frac{1}{2}$	•	1	•	2	3	∞
Minor planets: Sun, Mercury, Venus, Earth, Mars, Jupiter.....	$p=0$	$\frac{1}{3}$	•	$\frac{2}{3}$	1	•	2	•	∞
Satellites of Jupiter: Jupiter, Io, Europa, Ganymede, Callisto, Outer Space.....	$p=0$	•	$\frac{1}{2}$	$\frac{2}{3}$	1	•	2	•	∞
Satellites of Uranus: Uranus, Ariel, Umbriel, Titania, Oberon, Outer Space.....	$p=0$	•	$\frac{1}{3}$	$\frac{2}{3}$	1	$\frac{3}{2}$	•	•	∞

Frequency.....	12	6	7	4	10	2	8	4	12
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Carrying the enquiry forward, more by analogy than by direct comparison, Professor Goldschmidt sees the Law of Complication underlying still further groups of natural appearances; among

¹⁸ The chords are here named according to conventional musical theory.

these are certain processes in organic evolution and even some aspects of human physiology and psychology, especially those concerned with the perception of harmonious things. The general conclusion is that the development of the manifold from the simple, by complication, is a universal process. In the realm of sound complication leads literally to an harmonious relation of parts; and therefore, in a more general sense, the universal action of complication points to an harmoniously constructed universe.

The belief in an harmonious universe is not without precedent. Pythagoras knew exactly the numerical relations of the vibration periods of musical intervals. Fully convinced that "number is the essence of things," he dreamed of a universal harmony which could be expressed in rational numbers. With very imperfect knowledge of the solar system, Ptolemy applied himself to finding harmonious relations in the motions of the planets. With much more exact knowledge, Kepler made an extended search for the "harmony of the spheres." This he found, not in the relations of the radii of the orbits of the planets, but in the ratios of their greatest and least apparent angular velocities as seen from the sun, that is in the eccentricities of the orbits. Each planet was thus associated with a definite musical interval. A connection between crystals and the planets appears also in Kepler's fanciful disposition of the five perfect Platonic figures (forms in the cubic system) among the orbits of the planets.¹⁹

In his discovery of a definite number law underlying several extensive and widely different groups of natural phenomena, Goldschmidt has given new significance and precision to the ancient conception of universal harmony. The close approach of the series discussed to an exact mathematical series cannot possibly be the result of coincidence. Adopting the most conservative attitude, we must concede that the discussion points not only to some pervasive principle of rationality underlying the physical phenomena considered, causing certain measures of these phenomena to have simple rational values, but also to a definite preferred order of frequency in these simple rational measures. In the phenomena considered these measures are functions of length; but it is not unlikely, as Goldschmidt believes to be the case in the crystallographic series, that the measures are really functions of force. A similar principle of rationality pervades chemistry, and there is much in the modern

¹⁹ Ioannis Keppleri, *Harmonices Mundi*, Lincii Austriae, v, p. 207, 1619.

outlook in physics to suggest that its fundamentals will eventually be expressed in simple rational numbers.

In crystallography the Law of Complication is evidently a form of the Law of Rationality, and it has proved to be a more general form than the Law of Simple Rational Intercepts and Indices, since it has been found to underlie the hitherto wholly anomalous observations on calaverite. The Law of Complication has furthermore a genetic significance which the older law does not possess; in the hypothesis of crystal development by the interaction of principal crystal forces we have what may be regarded as a first approximation to an explanation of the external form and habit of crystals, an aspect of crystallography—and the one which is after all the most important to the morphologist—which is illuminated neither by the older law nor by röntgenographic studies concerned with the internal arrangement of crystalline matter.

APPENDIX

Since the above was written, the following publication has been received:

V. Goldschmidt, *Der Planet Pluto und die Harmonie der Sphären*, *Heidelberger Akten der von Portheim-Stiftung*, **18**, 22 pp., 1932.

In this paper it is shown that the recently discovered planet Pluto, whose orbit has a mean radius of nearly 40 astronomical units, fits squarely into the complication series of the major planets, giving the series:

SUN	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO	OUTER SPACE
$p = 0$	$1/2$	1	2	3	4	∞

The new planet thus affords striking proof of the validity of the Law of Complication in the arrangement of the bodies of the solar system.

Professor Goldschmidt briefly reviews his earlier studies of harmonious arrangements in crystallography, music, colour and cosmic space, and gives a generally applicable definition of harmony:

"Harmony is an arrangement or grouping characterized by the harmonic (complication) series and caused by complication" (*op. cit.*, p. 17, *trans.*).

The review which we have given is concerned mainly with the numerical basis of Professor Goldschmidt's theory of complication and harmony. To obtain a just conception of the full application and philosophical import of the theory the reader must turn to the original writings. The following list includes those referred to and others not cited:

Victor Goldschmidt (Heidelberg):

1897: Über Entwicklung der Krystallformen, *Zeitschrift für Krystallographie*, **xxviii**, pp. 1-35; 414-451.

1901: *Über Harmonie und Complication*, Berlin.

1904: Über harmonische Analyse von Musikstücken, *Annalen der Naturphilosophie* (Ostwald), **iii**, pp. 449-508.

1905: Beiträge zur Harmonielehre, *Annalen der Naturphilosophie* (Ostwald), **iv**, pp. 417-442.

1906: Über Harmonie im Weltraum, *Annalen der Naturphilosophie* (Ostwald), **v**, pp. 51-110.

1909: Kometen als kosmische Analytiker, *Annalen der Naturphilosophie* (Ostwald), **viii**, pp. 477-482.

1912: Harmonie im Reich der Planetoiden, *Annalen der Naturphilosophie* (Ostwald), **xi**, pp. 383-392.

1919: *Farben in der Kunst*, Heidelberg; second edition, 1929.

1921: Complication und Displcation, *Heidelberger Akademie Sitzungsberichte*, **A**, **12**, pp. 1-90.

1923: *Materialien zur Musiklehre*, vol. **i**, Heidelberg.

1925: *Materialien zur Musiklehre*, vol. **ii**, Heidelberg.

1932: Der Planet Pluto und die Harmonie der Sphären, *Heidelberger Akten der von Portheim-Stiftung*, **18**, 22 pp.

PUMPELLYITE FROM CALIFORNIA

JOHN IRVING, M. VONSEN AND F. A. GONYER

ABSTRACT

Two varieties of pumpellyite, differing slightly in optical properties from the mineral as originally described, but chemically like it are described from near Petaluma, California, where they occur associated with lawsonite in glaucophane schists. Analyses of these two varieties, one green in color, one brown, are given and their optical properties are tabulated. A new formula for the mineral is suggested. No material was obtained on which crystal measurements, other than the cleavage angle, could be made.

The mineral pumpellyite was originally described in 1925 by C. Palache and H. E. Vassar¹ as occurring along with epidote in amygdaloidal cavities in a lava from Lake Superior. It is, essentially, a hydrated calcium aluminum silicate, with minor amounts of iron, magnesium and manganese. It has since been recorded from Haiti, again from an amygdaloidal lava, a description of which, by Burbank,² gave slight variations in some of the optical constants from those of the original material. No chemical analysis of the mineral from Haiti has been made.

The material to be described in this communication was collected by Mr. M. Vonsen of Petaluma, California. It occurs in a glaucophane schist and is of two varieties. One of these is dull green in color and forms, along with lawsonite, veins in glaucophane schist at Mill Creek. At this locality the schist is cut by two sets of veins, one consisting of lawsonite and pumpellyite, the other of lawsonite alone. The latter are cut sharply by the former, so that there appear to be two ages of lawsonite in the veins. In the lawsonite-pumpellyite veins, the pumpellyite is seen to be replacing the lawsonite. The second variety of pumpellyite is brown in color, fibrous, and occurs as tufts or radiating aggregates in the glaucophane schist itself. This material was collected from near Skaggs.

Little difficulty was encountered in separating the mineral. The specific gravity of the green variety was found to be 3.18 while the brown gave a result of 3.22. Until the analyses were known they were considered to be new minerals as there is variation in appearance and occurrence in the two varieties, nor does either coin-

¹ Palache, Charles and Vassar, Helen E., Some minerals of the Keweenawan copper deposits, *Amer. Mineralogist*, vol. x, p. 412, 1925.

² Burbank, W. S., Additional data on the properties of Pumpellyite, *Amer. Mineralogist*, vol. xii, p. 421, 1927.

cide with the properties of the previously described pumpellyites.

The properties of pumpellyite from the different localities are given in tabular form below for comparison.

TABLE OF OPTICAL PROPERTIES OF PUMPELLYITE

	Pumpellyite from Lake Superior	Pumpellyite from Haiti	Pumpellyite, green from Mill Creek	Pumpellyite, brown from Skaggs
Indices of Refraction	$\alpha = 1.698$ $\beta = 1.700$ $\gamma = 1.708$	1.700 1.707 1.718	$1.679 \pm .003$ 1.680 1.692	$1.677 \pm .003$ 1.678 1.690
Optical Character	+	+	+	+
Dispersion 2V	$\rho < v$ strong large	$\rho < v$ strong large $75^\circ - 80^\circ$	$\rho < v$ strong $40^\circ \pm 2^\circ$	$\rho < v$ strong $38^\circ \pm 2^\circ$
Optical Orientation	Y = elong.	Y = elong. = b ? Z \wedge cleavage (001) = 31°	Y = elong. = b X \wedge $a = 12^\circ$	Y = elong. = b X \wedge $a = 12^\circ$
Form	Fibrous	Prismatic parallel to Y	Fibrous, twinned; twin plane and composition plane = (001)	Fibrous, occa- sional twins; twin and comp. plane = (001)
Cleavage	Perfect nearly normal to x (basal)	Basal well de- veloped	Basal almost normal to Z. (100) im- perfect	Basal almost normal to Z. (100) im- perfect
Color	green	bluish green	green	brown
Pleochroism	X = colorless Y = bluish green Z = colorless	colorless bluish green colorless	colorless pale green colorless	colorless brownish yellow colorless

The best cleavage of the pumpellyite *i.e.* the face on which the majority of fragments in an immersion lie, gave an off-centered acute bisectrix figure, but in thin sections of the mineral no very pronounced cleavage could be identified. Several fibres, measured on a goniometer showed two faces at 45° to one another and these were thought to be cleavage faces. In thin sections, however, no such cleavage could be made out. It is possible that the measurement was made on crystal faces, but no reflections other than these two were obtained, nor did any of the fibres show crystal terminations.

With the green variety twinning is visible in thin sections cut across the fibres, and the optical orientation in relation to the composition plane was determined by use of the Fedorov stage. Such sections are shaped like oak leaves with the composition plane down the center. The composition plane was found to be the twin plane also, and is oriented parallel to $Y = b$ and almost perpendicular to Z . The angle between X and the twin plane is 12° . The cleavage is parallel to the twin plane, and if we consider it as basal, the twin plane is (001) and $X \wedge a = 12^\circ$.

In sections parallel to (100) the twinning is liable to escape notice as both individuals show parallel extinction and differ only slightly in birefringence.

Twinning is less common in the brown variety, but the orientation in relation to the elongation is identical.

Analyses of the two varieties by F. A. Gonyer are quoted below along with that of the Lake Superior material.

Comparing the analyses we see that going from A to C we have a

TABLE OF CHEMICAL ANALYSES OF PUMPELLYITE

- A. Pumpellyite from Lake Superior, analyzed by H. E. Vassar³
- B. Pumpellyite from Mill Creek, green, analyzed by F. A. Gonyer
- C. Pumpellyite from Skaggs, brown, analyzed by F. A. Gonyer
- D. Composition of Pumpellyite calculated from the formula $6\text{CaO} \cdot 3\text{Al}_2\text{O}_3 \cdot 7\text{SiO}_2 \cdot 4\text{H}_2\text{O}$.
- E. Composition of Pumpellyite calculated from the formula $\text{Ca}_4(\text{Al}, \text{Mg})_6\text{Si}_6\text{O}_{23}(\text{OH})_3 \cdot 2\text{H}_2\text{O}$.

	A.	B.	C.	D.	E.
SiO_2	37.18	38.01	37.63	37.0	38.2
TiO_2		0.21	0.41		
Al_2O_3	23.50	25.88	27.14	27.0	27.3
Fe_2O_3	5.29	1.11	—		
FeO	2.09	2.90	3.25		
MnO	0.13	0.17	1.03		
MgO	3.18	1.81	1.47		4.4
CaO	23.08	22.70	21.49	29.6	23.8
Na_2O	0.19		0.46		
		0.46			
K_2O	tr		0.08		
$\text{H}_2\text{O} +$	6.28	6.64	7.27	6.3	6.7
$\text{H}_2\text{O} -$	0.06		0.12		
	100.97	99.89	100.35	99.9	100.4

³ *Loc. cit.*, p. 414.

series in which the aluminum content increases, showing less replacement by ferrous and ferric iron, manganese and magnesium, while more lime is replaced by alkalis. Both these progressive changes would lead to a lowering of the indices of refraction, which is in accord with the observations.

The increase in titanium which offsets these variations is too slight to have any material effect. The brown variety probably owes its color to its content of manganese as it is free from ferric iron and on heating turns a bluish color. The green material on heating turns brown.

The atomic proportions derived from these analyses as shown in the table following would lead to the formula $\text{Ca}_4\text{R}_6\text{Si}_6\text{O}_{23}(\text{OH})_3 \cdot 2\text{H}_2\text{O}$, where $R = (\text{Al}:\text{Mg}+\text{Fe}) = 5:1$.

CALCULATION OF FORMULA

A.	B.	C.
Atomic proportions of:		
Si 616 $=6 \times 103$	Si 633 $=6 \times 106$	Si 627 6×105
Al 460	Ti 3	Ti 5
Fe 66 $\left. \begin{array}{l} 526 \\ 29 \end{array} \right\} 636 = 6 \times 106$	Al 506 $\left. \begin{array}{l} 523 \\ 14 \\ 40 \end{array} \right\} 610 = 6 \times 102$	Al 532 $\left. \begin{array}{l} 537 \\ 45 \end{array} \right\} 634 = 6 \times 106$
Mn 2 $\left. \begin{array}{l} 110 \\ 79 \end{array} \right\}$	Fe 14	Fe 45
Mg 79	Fe 40	Mn 15 $\left. \begin{array}{l} 97 \\ 37 \end{array} \right\}$
Ca 411	Mn 2 $\left. \begin{array}{l} 87 \\ 45 \end{array} \right\}$	Mg 37
Na $\left. \begin{array}{l} 417 \\ 6 \end{array} \right\} = 4 \times 104$	Mg 45	Ca 383
K 6	Ca 405	Na $\left. \begin{array}{l} 399 \\ 16 \end{array} \right\} = 4 \times 100$
H 704 $= 7 \times 101$	Na $\left. \begin{array}{l} 419 \\ 14 \end{array} \right\} = 4 \times 105$	K $\left. \begin{array}{l} 820 \\ 2959 \end{array} \right\}$
O 2897 $= 28 \times 103$	H 738 $= 7 \times 105$	H 820 $= 7 \times 117$
	O 2920 $= 28 \times 104$	O 2959 $= 28 \times 106$

A. Pumpellyite from Lake Superior.

B. Pumpellyite from California, green.

C. Pumpellyite from California, brown.

In the formula given to the original pumpellyite, $6\text{CaO} \cdot 3\text{Al}_2\text{O}_3 \cdot 7\text{SiO}_2 \cdot 4\text{H}_2\text{O}$ the ferric iron was calculated in with the alumina and the ferrous iron, magnesia, manganese, and alkalis taken along with the lime. The analyses of both varieties of the Californian pumpellyite fit this formula moderately well, but it was found that by calculating the alumina with the ferric and ferrous iron, magnesium and manganese, and only the alkalis with the lime,

as *x*-ray analysis has shown to be the more natural substitution,⁴ we obtain the formula given above which is in closer agreement with the three analyses. In this form the relation with zoisite, $\text{Ca}_4\text{Al}_6\text{Si}_6\text{O}_{24}(\text{OH})_2$, is brought out. The pumpellyite might be considered as zoisite with (MgH) replacing aluminum and with the addition of two molecules of water. This close relation is reflected in the similarity of their crystallographic and optical properties. The main difference is in indices of refraction which are lower in the case of the pumpellyite, a result which might be expected from the increase in water content.

Professor Palache has requested the writers to point out that in the 1925 paper on pumpellyite,⁵ the formula for zoisite was inadvertently misquoted. The accepted formula is, as given above, $4\text{CaO} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

The hydration curve of pumpellyite would throw much light on the role played by the water in its composition, but the apparatus necessary to make this determination was not available.

In conclusion, the writers wish to express their indebtedness to Professor E. S. Larsen and to Mr. Berman for checking the determinations of optical constants.

⁴ Wherry, E. T., Volume isomorphism in the silicates, *Amer. Min.*, vol. 8, 1923, p. 2.

⁵ *Loc. cit.*, p. 414.

THE DEUTERIC AND LATER ALTERATIONS OF THE UNCOMPAHGRITE OF IRON HILL, COLORADO

ESPER S. LARSEN¹ AND E. A. GORANSON

ABSTRACT

The uncomphagrite, a coarse-grained melilite rock from Iron Hill, Colorado, offers an unusually good opportunity to follow a series of reactions and replacements of melilite and other minerals ranging from those caused by the residual liquor of the crystallizing magma before it separated from the crystal-mesh to those caused by hydrothermal solutions that gathered into fractures and were probably relatively dilute.

The first replacement formed a very small amount of light colored perovskite in narrow rims, associated with some phlogopite, about the darker colored magmatic perovskite and to a less extent about magnetite. This was followed by a larger scale replacement of melilite by a dark titaniferous garnet, that formed either irregular grains or more commonly, rims about perovskite, magnetite, and pyroxene; and to a less extent about melilite grains. In part the garnet replacement was concentrated in veinlike masses. The replacement of melilite by perovskite and probably much of that by garnet was brought about by the residual liquor of the magma before it had moved from the crystal-mesh. A part of the garnet was deposited by solutions moving in fractures.

The garnet became lighter colored and lower in titanium content toward the end of its period of deposition and it was joined by vesuvianite and this in turn by a colorless diopside. The replacement of melilite by vesuvianite and diopside took place along fractures in the rock, was unevenly distributed, and locally yielded large bodies.

The next alteration was to sheaves of a finely fibrous new mineral, called juanite. Juanite was followed by an undetermined fibrous mineral (mineral A) and this by cebollite. The cebollite, was, in turn, followed by a second undetermined mineral (mineral B).

Brunatellite was found locally. Hastingsite replaced the pyroxene in small amount and soda tremolite and aegirite were formed in seams; they were probably a result of the intrusion of the uncomphagrite by a pyroxenite.

In the replacement of melilite by vesuvianite and diopside, by juanite, and by cebollite, there was very little change in chemical composition.

Juanite occurs in fibrous growths. It is probably orthorhombic with Z parallel to the length. It appears to be optically positive with a moderate axial angle. $\alpha = 1.640$; $\gamma = 1.647$. Fusibility about 3; Hardness $5\frac{1}{2}$. It has the composition $10\text{CaO} \cdot 4\text{MgO} \cdot \text{Al}_2\text{O}_3 \cdot 11\text{SiO}_2 \cdot 4\text{H}_2\text{O}$.

CONTENTS

INTRODUCTION.	344
THE UNCOMPAHGRITE AND ITS GEOLOGICAL OCCURRENCE.	344

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THE ALTERED UNCOMPAHGRITE.....	345
Late perovskite.....	345
Titaniferous garnet.....	345
Vesuvianite and diopside.....	347
Juanite.....	349
Undetermined mineral A.....	349
Cebollite.....	349
Undetermined mineral B.....	350
Brugnatellite.....	350
Zeolites.....	350
Amphibole, chlorite, aegirite, and mica.....	350
SUCCESSION OF ALTERATIONS.....	351
CHEMISTRY OF THE ALTERATION PRODUCTS.....	353
JUANITE, A NEW MINERAL.....	354
NEW OPTICAL DATA ON CEBOLLITE.....	356

INTRODUCTION

The field data and the material described in this report were collected by the senior author while making a geological map of the San Juan region, Colorado, for the United States Geological Survey. The laboratory work was carried on in the Department of Mineralogy and Petrography of Harvard University.

The Iron Hill stock of alkaline rocks is located in Gunnison County, Colorado, about 20 miles south 20° west of the town of Gunnison and a few miles southeast of Powderhorn Post Office.

THE UNCOMPAHGRITE AND ITS GEOLOGICAL OCCURRENCE

The alkaline stock is about 8 miles across. It intruded pre-Cambrian gneisses and granitic rocks, is overlain by the Tertiary volcanics, and as the minerals peculiar to the stock are found in the heavy concentrates of a nearby sandstone of Jurassic age, it is believed to be pre-Jurassic. The oldest rock within the stock is a great mass of marble about a mile across. This was intruded by the uncompahgrite. The main mass of the stock is a pyroxenite of somewhat variable composition, carrying masses of magnetite-perovskite rock. This pyroxenite intruded the uncompahgrite and was in turn intruded by dikes and less regular bodies of ijolite. The next intrusion was a soda syenite, followed by a nepheline syenite, and the last intrusions were dikes of nepheline gabbro and a gabbro carrying some quartz and orthoclase. Numerous veins of calcite carrying some aegirite, amphiboles, phlogopite and other minerals are present.

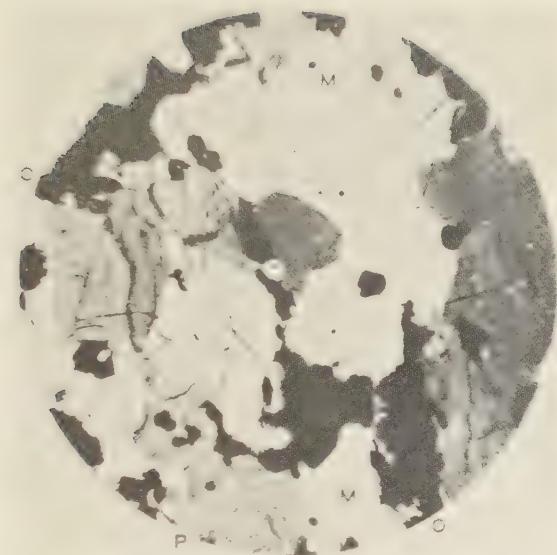


FIG. 1. The fresh uncompahgrite, melilite (M), primary pyroxene (P), and iron ore (O). Crossed nicols $\times 35$.



FIG. 2. The fresh uncompahgrite showing primary pyroxene (P) with corroded outlines. Crossed nicols $\times 20$.



FIG. 3. Irregular patches of garnet (G) in melilite (M). The right-hand grain of garnet shows the two-color varieties, the brown center and the olive-green border. Partly crossed nicols $\times 70$.

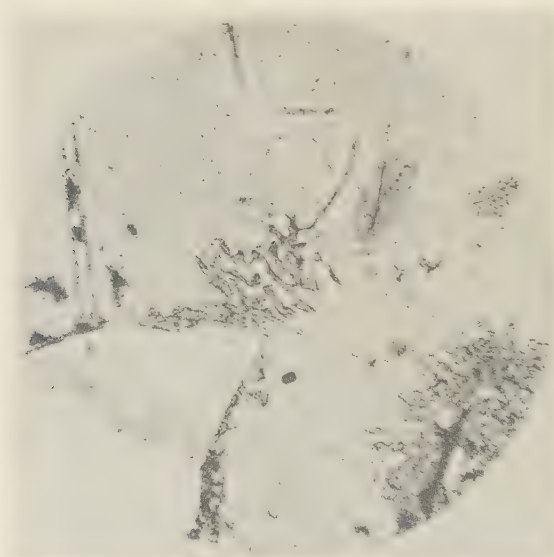


FIG. 4. Micrographic growth of garnet in melilite. partly crossed nicols $\times 70$.

The uncompahgrite is present only in the drainage area of Beaver Creek, north of Iron Hill, in several disconnected masses, the largest of which is about a mile long and half a mile wide. The fresh rock is blue-gray in color and consists of about two-thirds of melilite with the balance chiefly green diopside, magnetite, perovskite, and apatite. The grain size varies greatly and is determined chiefly by the melilite, which varies from less than a millimeter to over 50 centimeters in cross section. In the finer-grained varieties the texture is granular, while in the coarse varieties the huge melilite crystals enclose the other constituents. Primary (?) calcite is present in small amount as an interstitial constituent, and commonly shows reaction rims of garnet. Very pale green or brown phlogopite which crystallized very late is present in small amount as plates or irregular grains, or as rims around perovskite, apatite, and magnetite. Where it adjoins perovskite it shows pleochroic halos. Nepheline, mostly altered, is a rare constituent. Typical photomicrographs of the unaltered medium-grained uncompahgrite are shown in figures 1 and 2.

THE ALTERED UNCOMPAHGRITE

Though considerable parts of the uncompahgrite show little alteration, much of it is partly altered and some parts of it are almost completely altered. The nepheline, where present, is the mineral most susceptible to alteration; the melilite is also altered, whereas the other minerals are rather resistant. The alteration may replace either large masses of the melilite or be confined to streaks, seams, or veinlets, giving the rock a streaked or banded appearance.

LATE PEROFSKITE

The first alteration, which shows in only a few specimens, formed narrow rims—a fraction of a millimeter across—of perovskite about both magnetite and primary perovskite next to melilite. This late perovskite is yellow-brown and much lighter in color than the early perovskite. Small grains of perovskite are either associated with, or incorporated in small bands of garnet which surround magnetite.

TITANIFEROUS GARNET

Following the late perovskite, garnet formed either in vein-like masses, in individual euhedral or subhedral crystals (figure 3) or in irregular borders about the earlier minerals (figures 5 and 11).

It formed borders most commonly about magnetite, perovskite, and calcite, less commonly about mica and apatite, and rarely about pyroxene and coarse calcite. In some specimens pale phlogopite is associated with this garnet and appears to have been formed with it. The garnet and mica also occur in narrow veinlets cutting the melilite or as narrow borders between melilite grains. In a few slides patches a millimeter across in large melilite crystals are made up of vermicular intergrowths of garnet and melilite much like symplektitic or micrographic textures (figure 4). In one section a similar intergrowth of garnet and primary pyroxene was found. The main part of the garnet, especially that next the magnetite, is dark-brown under the microscope, has an index of refraction of 1.95 and is a titaniferous andradite. The borders are light olive-green to nearly colorless and have an index of refraction as low as 1.85. The two varieties grade into one another (figure 3).

In part the phlogopite was later than the garnet as it formed narrow ragged fringes about garnet crystals. In places the mica appears to have replaced the garnet.

In several specimens magnetite is surrounded by a narrow layer of pale perovskite, about this is a narrow layer of garnet, and about the latter a less regular layer of phlogopite. Fresh melilite is next the phlogopite.

For the most part the garnet replaced melilite, but it may to a small extent have replaced other minerals. In some specimens the garnet might be considered as due to a reaction between melilite and magnetite, but in others it is present about perovskite, apatite, and all other primary minerals as well as between the melilite grains and in veinlets cutting the melilite grains. This replacement is irregularly, but widely distributed, and differs in amount from place to place. In most specimens only a few per cent of garnet and mica were formed but in some, 30 per cent or more; and in a few veinlike bodies, up to 20 centimeters or more across, over 50 per cent of garnet was formed. In all cases the garnet is surrounded by fresh melilite, unless the melilite has been later altered.

A vein about 10 centimeters wide cutting the uncompahgrite exposed in the bed of the gully south of Beaver Creek, three-quarters of a mile above the mouth and about 250 yards below the fork of the gully, was formed by moving solutions. The borders of this vein are made up chiefly of the brown garnet with some pale green phlogopite, pleochroic green chlorite, calcite, and fibrous zeolites.

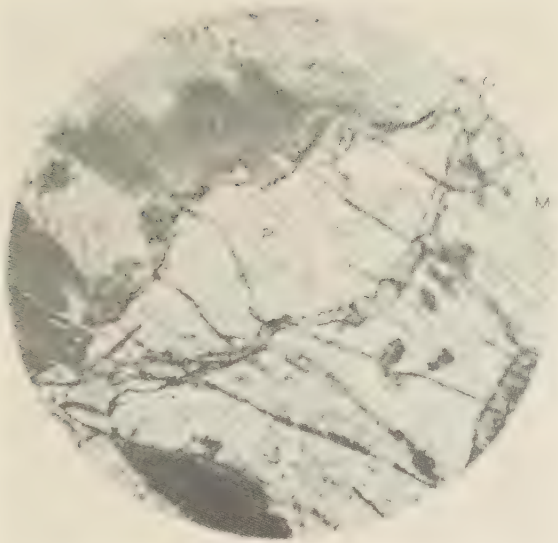


FIG. 5. Garnet (G) bordering an irregular grain of primary pyroxene (P); the outer surrounding mineral is melilite (M) partly altered to juanite (J) etc. Partly crossed nicols $\times 70$.

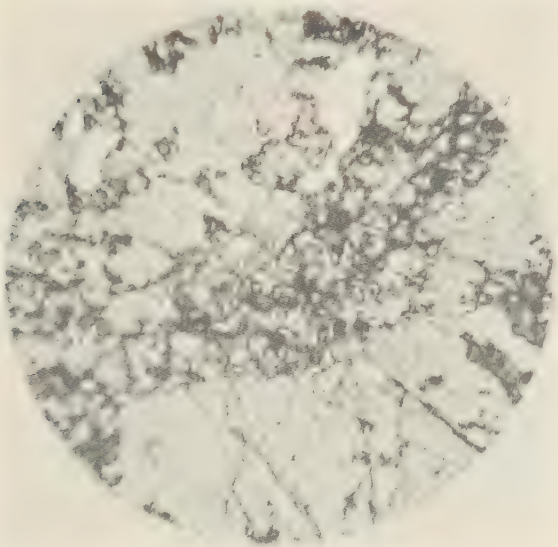


FIG. 6. A large grain of primary pyroxene being replaced by vesuvianite (V). Partly crossed nicols $\times 40$.

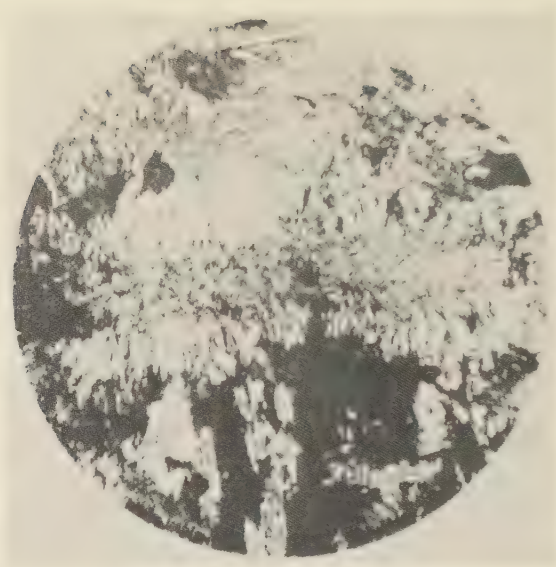


FIG. 7. Secondary diopside and vesuvianite in a highly altered uncompahgrite. The diopside is in fibres arranged at right angles to the fracture crossing the centre of the slide. Crossed nicols $\times 70$.

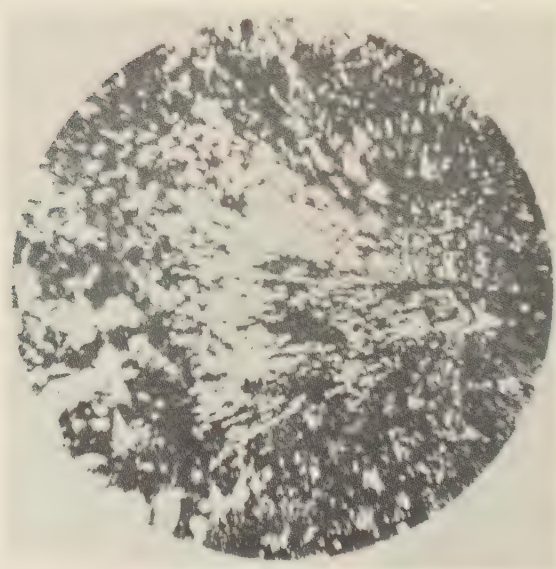


FIG. 8. Radiating secondary diopside (light) and vesuvianite (dark) in the altered uncompahgrite. Crossed nicols $\times 40$.

Next to this zone and grading into it is a zone made up mostly of coarse vesuvianite in which are embedded crystals of monticellite. The center is made up of large grains of cancrinite containing embedded grains of monticellite² and some of the brown garnet.

At the time of the deposition of the garnet and phlogopite the magma must have been almost completely crystalline and the amount of interstitial liquid could not have exceeded a few per cent. The formation of the garnet may have been partly caused by the residual interstitial liquid before that liquid had moved from the interstices between the crystals but the uneven distribution of the replacement and particularly the presence of the vein-like bodies of garnet rock show that the liquid had moved somewhat and had collected in fractures and other channelways. It seems probable that this replacement was transitional between a truly magmatic reaction and a hydrothermal reaction (due to moving solutions enriched in water).

VESUVIANITE AND DIOPSIDE

Following the deposition of the garnet, but in part contemporaneous with it, vesuvianite and colorless diopside began to replace melilite. In some large bodies of uncomphagrite the melilite is completely replaced, in other large bodies the melilite is unaltered except for scattered thin veinlets of the secondary minerals. In places the veinlets are so abundant that only remnants of fresh melilite remain. The alteration took place chiefly from fractures in the rock and worked out from them (figure 7). In part it began at the borders of the melilite grains, or about grains of magnetite or other minor constituents as centers, and spread out forming spherulitic bodies of the secondary minerals (figures 8 and 12). In one specimen a thin network of diopside separates the melilite grains and areas of diopside enclosing several melilite grains give simultaneous extinction.

The minerals of this replacement are colorless diopside, colorless garnet, and vesuvianite with some calcite. Chlorite, muscovite, titanite, and amphibole are in places associated with these minerals and are probably of late origin. The minerals are in fine intergrowths in many of the rocks, in part resembling micropegmatitic intergrowths. In part the diopside is in plumose or arborescent aggregates penetrating the garnet or vesuvianite and in part it formed in

² Larsen, E. S. and Foshag, W. F., Cancrinite as a high temperature hydrothermal mineral from Colorado: *Am. Min.*, **11**, 300-303, 1926.

widely radiating aggregates from the grains of magnetite, apatite, perovskite, and other minerals or from the plane of the fracture along which the altering solutions moved.

Though in most places the three minerals are so intimately intergrown as to leave no reason to believe that one preceded the other, locally garnet preceded vesuvianite and diopside was last. Veinlets of diopside cut the vesuvianite and crystals of the diopside project into the vesuvianite from the walls of veinlets.

In some of the rock where the replacement is most complete the replaced rock is a coarse-grained aggregate of garnet, vesuvianite, diopside, and some calcite with the original minerals of the uncomphagrite, except the melilite. In these aggregates the minerals tend to intergrow much as they do in the lime-silicate hydrothermal contact metamorphic replacements of limestone. Indeed, these rocks were at first called contact metamorphic limestones but the fact that they still have all the original minerals of the uncomphagrite, except melilite and nepheline, and that the alteration of uncomphagrite can be found in all stages of development, shows conclusively that they represent altered uncomphagrite.

Vermicular or symplectitic intergrowths between the secondary minerals, or between them and the primary minerals, are common. In one slide a peculiar vermicular intergrowth of melilite and diopside occurs around magnetite and apatite grains where they are in contact with melilite. Commonly between the magnetite and this vermicular growth is a narrow zone of light colored perovskite, the latter generally partly altered to leucoxene. Along the adjacent melilite grain borders are small irregular blebs of diopside but they do not form the delicate intergrowth. No diopside-hedenbergite similar to that which crystallized early from the uncomphagrite magma was noted in the two slides showing this texture.

In one slide tiny veins change character when passing through magnetite. These veins are formed of calcite where in altered melilite but in magnetite they are formed of vesuvianite in minute terminated prisms, jutting out at high angles to the walls with the centre of the vein composed of calcite. Another section shows a similar vein in altered melilite and magnetite with both calcite and vesuvianite along its entire course, the later, however, had not crystallized in prisms but occurred in streaks along the vein walls.

JUANITE

Following the replacement of melilite by vesuvianite and diopside, the remaining melilite was subjected to attack by four or more successive waves of hydrothermal alteration. In each wave the fresh melilite was chiefly attacked leaving the other mineral, including the older alteration products, practically unchanged. These changes took place along fractures and no large bodies of rock were affected, but the alterations were widespread and no large body of fresh uncomphagrite is free from veinlets of these alteration products. The relative ages of the different products are easily determined as veinlets of later types cut the older kinds.

The earliest of these alterations and probably the most abundant yielded a new fibrous, nearly white mineral, called juanite. It is arranged in sheaf-like aggregates about a millimeter long. In part this alteration to juanite follows cleavages or crystal boundaries of the melilite but for the most part its position does not seem to be determined by any structural control (figures 9 and 10). The mineral is described in a later section. It has a composition much like that of the melilite but some soda has been removed and some water added.

UNDETERMINED MINERAL A

Sheaf-like fibrous aggregates, much like those of juanite but with a somewhat stronger birefringence and lower indices of refraction, are commonly mixed with the juanite sheaves in small amount and in one section they make up a considerable part of the mass. This will be called Mineral A. The aggregates of Mineral A are commonly clearer than the juanite and in places grow out from grains of apatite. Small veinlets of Mineral A traverse the juanite and it is therefore younger, or perhaps in part contemporaneous with the juanite.

CEBOLLITE

The next alteration product to form was cebollite, described in 1914 by Larsen and Schaller³ from this area. The cebollite, colorless in thin section and minutely fibrous in habit, is definitely related to

³ Larsen, E. S. and Schaller, W. T., Cebollite, a new mineral: *Jour. Wash. Acad. Sci.*, IV, pp. 480-2, 1914. Kranck, E. H., On turjaite and the ijolite stem of Turja, Kola: *Fenia.*, 51, No. 5, p. 27, 1928. Tilley, C. E. and Harwood, H. F., The dolerite-chalk contact of Scawt Hill, Antrim: *Min. Mag.*, 22, pp. 455-6, 1931.

fractures in the melilite, and forms only in close proximity to these fractures (figs. 10, 11, and 12). The cebollite fibres form along the walls of the fractures with their long axes usually perpendicular or at high angle to the fracture direction. In one section melilite, altered almost completely to juanite, was cut by a fracture at an angle to the cleavage of the melilite, and cebollite had formed along this fracture (fig. 10); the juanite fibre aggregates had replaced the melilite with their long axes parallel to the cleavage of the host and the cebollite was replacing the juanite in like manner. The cebollite is associated with a colorless, granular, isotropic mineral that resembles garnet but has a low index of refraction ($n = 1.67$).

UNDETERMINED MINERAL B

An alteration product called Mineral B found in only one thin section, occurs in a tiny veinlet cutting the juanite and the cebollite. The vein has tiny apophyses. The mineral is fine grained in the center of the vein but in the apophyses and along the borders of the veinlets it forms tiny needles arranged at an angle to the vein. This mineral has a low birefringence and the indices of refraction are between those of juanite and Canada balsam.

BRUGNATELLITE

A micaceous mass of nearly colorless brugnatellite, a hydrous carbonate of magnesium and ferric iron, was found as another kind of alteration of the melilite in small amount and in a few places, especially in the lower part of the gully south of Beaver Creek, and half a mile above the wagon road. It is present in vein-like streaks and as it is very soft it may be fairly common but rarely exposed. It is associated with a little calcite and hornblende.

The formation of the brugnatellite can not be placed in the sequence of alterations of the melilite. Its character indicates a very late hydrothermal alteration.

ZEOLITES

The nepheline, which is rare in the uncompahgrite, is largely altered to mixtures of analcite, cancrinite and a fibrous zeolite, probably natrolite or hydronephelite. In some parts the cancrinite has a low birefringence and is probably sulphatic cancrinite.

AMPHIBOLE, CHLORITE, AEGIRITE, AND MICA

The pyroxene, apatite, magnetite, perovskite, and mica, are mostly fresh, even where the melilite and nepheline have been com-

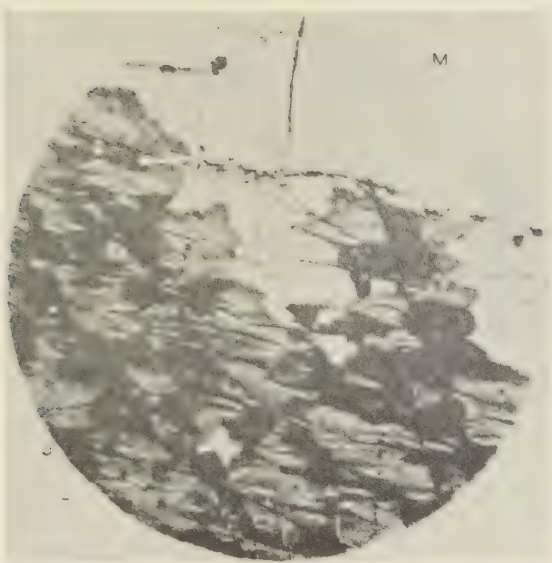


FIG. 9. Juanite (J) and alteration A attacking melilite. The long direction of the juanite sheaves are parallel to the cleavage of the melilite. Ordinary light $\times 20$.

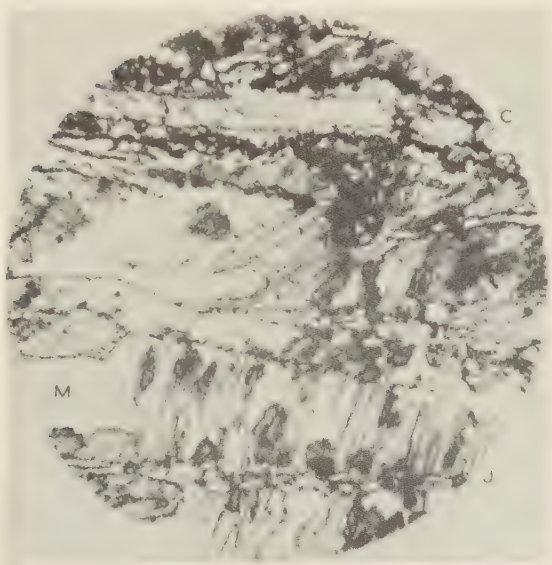


FIG. 10. Melilite (M) altered partly to juanite (J) and cut by a vein bordered by cebollite (C). The centre of the veinlet is mainly filled with fine-grained carbonate. Ordinary light $\times 20$.

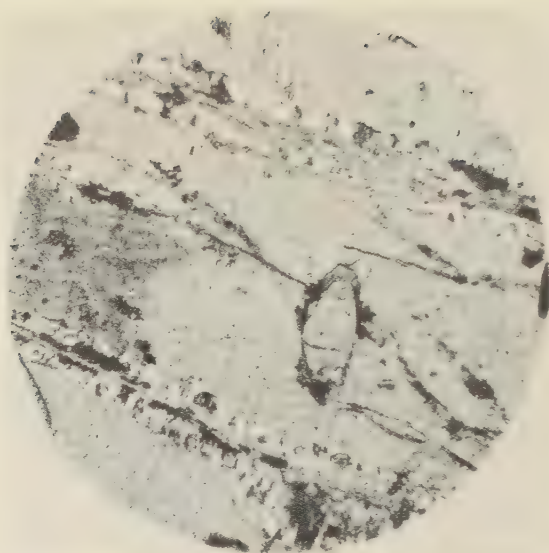


FIG. 11. Cebollite in veinlets cutting melilite; the cebollite fibres are arranged perpendicular to the veinlet. The centres of the veinlets are filled with fine-grained carbonate. Near the centre of the photomicrograph is a grain of apatite partly surrounded by garnet. Crossed nicol $\times 70$.

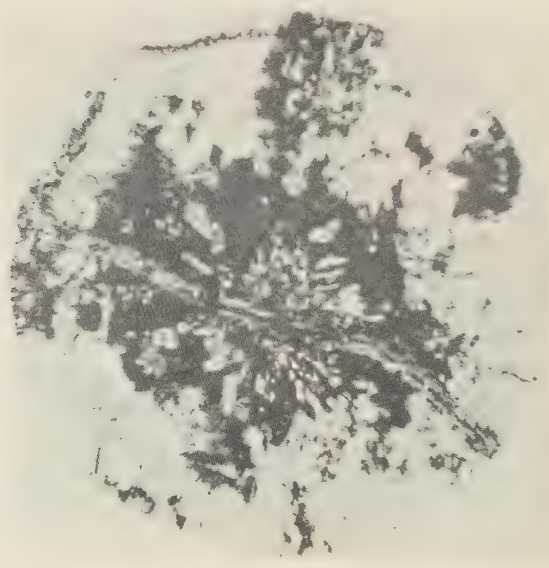


FIG. 12. A veinlet of cebollite and carbonate in melilite and vesuvianite. The dark mineral surrounding the veinlet is vesuvianite containing small prismatic crystals of secondary diopside. Crossed nicols $\times 70$.

pletely replaced. However, in places the pyroxene is more or less altered to magnesian hastingsite and to some green, uniaxial positive, chlorite. In part this alteration is scattered through the rock, in part along veinlets associated with calcite or zeolites that cut the altered melilite rock and are distinctly later than the vesuvianite-garnet-diopside rock. In one specimen the magnetite is bordered by a narrow zone of pale garnet, outside of this is a layer of pale green phlogopite, and beyond this a layer of blue-green amphibole.

In one specimen there are areas of coarsely crystalline nearly colorless phlogopite and calcite.

In some places aegirite, phlogopite, and an amphibole near sodatremolite are developed in the uncompahgrite.

SUCCESSION OF ALTERATIONS

The alteration of the uncompahgrite reveals a long sequence of changes from the intrusion of the magma to the present time.

After intrusion, on cooling and gradual loss of mineralizers, crystallization began with the formation of the diopside-hedenbergite. This was followed by the crystallization of magnetite and perovskite and then melilite. After the rock was almost completely crystallized the small amount of residual liquid, now greatly enriched in mineralizers, reacted with the crystallized minerals and first deposited a little perovskite about the magnetite and early perovskite, then dark titaniferous garnet about perovskite, magnetite, pyroxene, and apatite where these minerals were in contact with melilite and rarely about individual grains of melilite, or in veinlets cutting the older minerals. Later, phlogopite was formed with the garnet. The last of the garnet was lighter colored and poorer in iron and titanium. The preceding alterations were probably partly brought about by the residual magmatic liquid before it had moved from the interstices between the crystals but in part after the liquid had gathered into channelways.

Vesuvianite with colorless garnet next replaced the melilite and colorless diopside was later added to the vesuvianite. Calcite also was deposited to some extent. The liquids forming this vesuvianite-diopside rock were separated from between the crystal mesh and were clearly moving along fractures and only locally replaced the melilite. The products of this alteration are much like the high temperature hydrothermal contact metamorphic rocks derived from limestones and were no doubt produced under about the same temperature conditions.

Following the formation of the vesuvianite-diopside rock four or more other replacements of melilite, all by fibrous minerals growing out from fractures, affected parts of the melilite in regular order. Omitting the minor alteration products, the first was to juanite; then Mineral A. Later came the cebollite and finally Mineral B.

The replacements of melilite heretofore described appear to have been paulopost—caused by solutions that originated in the uncompahgrite magma itself. The evidence for this is:

1. The gradational character of the replacements beginning with reaction by the interstitial liquid.

2. The distribution of the replacement bodies without regard to contacts with the later pyroxenite.

3. The replacements are entirely different from those caused by the pyroxenite in intruded limestone, granite, and other rocks, which is characterized by soda-tremolite, aegirite, and phlogopite.

The sequence in the crystallization and later replacements in the uncompahgrite are summarized in table 1.

TABLE I
SEQUENCE IN THE CRYSTALLIZATION AND PAULOPOST REPLACEMENTS OF THE
UNCOMPAHGRITE. DECREASING TEMPERATURE →

	Magmatic	Magmatic reaction	Moving solutions
Diopside-hedenbergite	—————		
Magnetite	—————		
Apatite	—————		
Perovskite	—————		
Melilite	—————		
Green phlogopite	—————		
Carbonate (coarse-grained)	—————		
Perovskite (light-colored)		—————	
Garnet (titaniferous)		—————	
Garnet (light-colored)			—————
Green phlogopite			—————
Vesuvianite			—————
Diopside (colorless)			—————
Carbonate (medium-grained)			—————
Juanite			—————
Mineral A			—————
Cebollite			—————
Mineral B			—————
Carbonate (fine-grained)			—————

The brugnatellite was formed along fractures at a later time.

The rare hastingsite probably replaced the pyroxene after the intrusion of the pyroxenite as it is similar to the hastingsite that replaced the diopside of the pyroxenite. Likewise the rare vein-like bodies of aegirite and soda-tremolite are like the abundant alteration products caused by the pyroxenite and were no doubt formed by solutions from the pyroxenite.

CHEMISTRY OF THE ALTERATION PRODUCTS

The analyses of the melilite and of some of the alteration and replacement products, arranged in the order in which they are formed, are given in table 2. The first replacement product, perovskite, involved chiefly a substitution of silica by titania and took place on a very small scale. The second product, titaniferous garnet, formed partly in the very late magmatic stage but continued into the very early hydrothermal stage when the solutions were collecting and moving along fractures and other channelways. An analyses of a similar titaniferous garnet from the ijolite of the Iron Hill area is shown in table 2, column 2. This replacement of melilite by garnet involved a loss of silica, alumina, magnesia, lime, and alkalis, a large gain in ferric iron, and considerable gain in titania. Some of the alumina and magnesia may have gone into the biotite which commonly accompanies the garnet in small amount. The late light-colored garnet has much less titania and iron.

The third replacement appears to have followed the first closely and was clearly caused by moving solutions. In it, the melilite was replaced by a mixture composed chiefly of vesuvianite and diopside, with some carbonate, garnet, and other minerals. An analysis of uncomphagrite in which the melilite was completely altered to a coarse aggregate made up chiefly of vesuvianite and diopside is shown in column 3. It should be compared with analysis (1a) which represents fresh uncomphagrite. The approximate composition of this alteration product indicates, as does an examination under the microscope, a mixture made up about half of vesuvianite and a quarter of diopside. In this replacement there was little change in bulk composition—an oxidation of iron, a loss of nearly all the alkalis and a gain of about two per cent of water.

In the next large scale replacement to juanite, shown in column 4, there was a loss of alumina and alkalis, and a gain in magnesia and water, although the changes were not great.

In the alteration to cebollite, column 5, there was a considerable gain in magnesia and water, moderate loss in lime and alumina, an oxidation of the iron, and a replacement of part of the soda by potash.

TABLE 2
ANALYSES OF MELILITE, UNCOMPAHGRITE, AND REPLACEMENT PRODUCTS

	1	1a	2	3	4	5
SiO ₂	44.13	38.04	34.30	40.01	42.05	33.02
Al ₂ O ₃	10.80	6.34	4.46	5.41	5.19	14.02
Fe ₂ O ₃		8.45	24.09	7.12	3.26	3.43
FeO	2.04	5.90		1.08		0.21
MgO	4.35	7.81	0.52	8.89	9.52	4.69
CaO	34.63	27.19	31.06	30.99	34.68	35.72
Na ₂ O	3.40	2.16		0.60	1.06	2.57
K ₂ O	tr.	0.12		—	0.14	tr.
H ₂ O—		0.22		0.52	4.45	none
H ₂ O+	0.49	0.48		2.00		6.26
TiO ₂		1.98	5.08	1.00	none	
CO ₂		0.30		1.51		
P ₂ O ₅		0.24		0.88		
MnO	0.16	0.23		0.11	0.09	
S		0.02		0.06		
BaO						
SrO		0.26		0.21		
	100.00	99.74	99.51	100.39	100.44	99.92
Sp. Gr.	2.98	3.29	3.67	3.24	3.015	2.96

1. Melilite from Iron Hill computed free of impurities, W. T. Schaller, analyst.
- 1a. Typical fresh, fine-grained uncomphagrite, F. A. Gonyer, analyst.
2. Titaniferous garnet from ijolite of Iron Hill. Much like the garnet of the uncomphagrite. Approximate analysis by W. T. Schaller.
3. Uncomphagrite in which the melilite is altered to a coarse aggregate of vesuvianite, diopside, etc. F. A. Gonyer, analyst.
4. Juanite. F. A. Gonyer, analyst.
5. Cebollite. W. T. Schaller, analyst.

The approximate percentages of losses and gains in the major oxides and the changes in specific gravity that took place during the successive alterations are shown in table 3.

JUANITE,⁴ A NEW MINERAL

The occurrence and general character of juanite have been described in the preceding pages. It remains to add a few details.

⁴ Named from the San Juan Mountains of Colorado and pronounced huanite.

TABLE 3
APPROXIMATE CHEMICAL CHANGES IN THE REPLACEMENTS OF MELILITE

	Perovskite	Titaniferous garnet	Diopside and Vesuvianite	Juanite	Cebollite
SiO ₂	Large loss	-10		-2	-10
TiO ₂	Large gain	+ 5			
Al ₂ O ₃	Loss	- 6		-5	+ 3
Fe ₂ O ₃ } FeO }		+22	Oxidation	Oxidation	{Oxidation +3
MgO	Loss	- 4		+4	
CaO		- 3			
Na ₂ O	Loss	- 3	-2	-3	- 1
K ₂ O					
H ₂ O			+2	+4	+ 6
Change in Sp.Gr.	+Large	+Large	Little	+0.03	-0.02

The mineral is in such finely-fibrous aggregates that reliable optical data could not be had. The following measurements were made but they are due to aggregate effects. Parallel extinction; positive elongation; orthorhombic (?); optically+; $2V = 50^\circ$ (?); $\alpha = 1.640$; $\gamma = 1.647$; $\pm .003$; fusibility about 3; B. B. to a translucent glass; hardness 5.5; decomposed by acid.

Two analyses of juanite by F. A. Gonyer from different localities, both in the Beaver Creek drainage area follow. They are very similar and lead to the formula $4H_2O \cdot 10CaO \cdot 4MgO \cdot Al_2O_3 \cdot 11SiO_2$.

	1.	2.	Molecular proportions of average
SiO ₂	42.54	42.05	702 = 11×64
TiO ₂		none	
Al ₂ O ₃	5.65	5.19	53 } = 1×70
Fe ₂ O ₃ }	2.68 }	3.26	17 }
FeO }	0.56 }		8 }
MnO	0.11	0.09	} = 4×59
MgO	8.64	9.52	226 }
CaO	35.00	34.68	622 }
Na ₂ O	0.84	1.06	15 } = 10×64
K ₂ O	0.04	0.14	1 }
P ₂ O ₅	0.04		
H ₂ O—	0.18 }	4.45	
H ₂ O+	4.06 }		244 = 4×61
	100.34	100.44	
Sp.Gr.	3.01		

NEW OPTICAL DATA ON CEBOLLITE

New optical data on cebollite by Goranson are given below with the older data by Larsen.

	Goranson	Larsen
Optical Sign	+	+
Crystal System	Orth. (?)	Orth. (?)
2V	Med. Large	58° ±
Dispersion of 2V	$\rho > v$, weak	
$\alpha =$	1.592	1.595
$\beta =$	1.597	1.60
$\gamma =$	1.630	1.628

TWO NEW IRON METEORITES FROM CHILE AND TEXAS

CHARLES PALACHE AND F. A. GONYER

THE BAQUEDANO, CHILE, METEORITE

In 1930, the Harvard Mineralogical Museum obtained a new meteorite from Chile concerning which the following information was supplied by the vendor, Senor Custodio Rojas Arancibia of Antofagasta.

"The meteorite weighs 22 kilograms, is 31 cm. long, 21 cm. wide, and 10 cm. in thickness. It was found near the station Baquedano, situated in the kilometer 96 of the railroad from Antofagasta to Bolivia" (Translation).

The specimen was secured through letters exchanged in the course of a long correspondence between the late Dr. George P. Merrill of the National Museum and the owner of the meteorite assisted by Messrs. Thomas S. Horn and Sydney A. Browne, American Consul and Vice-Consul, respectively, at Antofagasta. The National Museum transferred it to the Harvard Collection in the course of exchange.

The station Baquedano appears in the Times Atlas map of Chile as a railroad junction point in Lat. $23^{\circ}13'$ South, Long. $69^{\circ}43'$ West. It lies in the northern part of the Atacama Desert.

The mass of iron is disc shaped; the upper face, Plate I fig. 1 is an irregular cone with minutely pitted surface; the lower surface, Plate I fig. 2, is nearly flat, with broad and shallow cavities and very little pitting. It is quite clear that the difference in detail of the two surfaces, shown in the side view, fig. 3, is due to the effect of sand blast action, the lower one, where it lay on the ground, having been protected from the wind which has developed on the exposed side the triangular pattern of the iron.

The iron had suffered considerable mutilation when received. The two largest holes near the center (fig. 1) are drill holes, the other holes near the edge more probably natural features, due to solution of pyrrhotite nodules. The tip of the cone was sawed off and a chisel cut made near the left hand edge. Plate II Fig. 3 also shows in the center rough chisel and hammer scars. Fig. 2 shows a cut and etched surface, revealing the octahedral pattern of the iron.

The etched surface shows bands of kamacite ranging in width from $1\frac{1}{2}$ to $2\frac{1}{2}$ mm. The iron is therefore to be classed as a coarse octahedrite. The kamacite lamellae are fairly straight and some extend, with interruptions, for as much as 10 cm. They are irregularly spaced. The taenite borders of kamacite plates are extremely thin. There is comparatively little plessite which is partly granular, partly finely lamellar.

Pyrrhotite is very sparingly present as thin plates and in one case as a circular nodule, shown in fig. 1.

Schreibersite is rather abundant in irregular plates disposed in elongated areas which show but poorly in the photograph.

This meteorite therefore shows no unusual features either in physical structure or in composition as discussed on a later page.

The present weight of the main mass of the Baquedano Iron is 20.15 kilograms. A small section of 880 grams is in the National Museum.

THE DEPORT, TEXAS, METEORITE

In March 1932, E. H. Sellards, Director of the Bureau of Economic Geology at the University of Texas, sent to the writer a small mass of iron which was reported to have been found by Mr. James Rhodes, one mile east of Deport, Red River County in northeastern Texas. The situation of this place is approximately in Lat. $33^{\circ}30'$ N. Long. $95^{\circ}18'$ West. More of the meteorite is said to be in Mr. Rhodes' possession but how much was found is not known.

The specimen weighed when received 1300 grams. As shown in Plate II fig. 4 it is an irregular lump of iron with shallow pittings. The end was sawed off and polished as shown in the photograph and etching revealed a well marked octahedral pattern. The width of the kamacite lamellae classify this iron also as a coarse octahedrite. The kamacite plates are closely spaced with a minute amount of taenite separating the lamellae. The amount of plessite is also very small so that the iron is composed almost wholly of kamacite. Schreibersite is fairly abundant, partly in irregular, nodular areas, more generally in rods which show in portions of the section as minute circular sections less than one mm. in diameter and therefore far too small to be visible in the photograph. These dots reflect the brilliant white lustre of schreibersite when the section is held in the proper position. Although no pyrrhotite is shown in the sec-

PLATE I



FIG. 1. Baquedano Meteorite. Top view.



FIG. 2. Baquedano Meteorite. Bottom view and etched section.

PLATE II



FIG. 3. Baquedano Meteorite. Side view.



FIG. 4. Deport Meteorite. View and etched section.

tion photographed, there are several nodules in other sections, the largest one cm. in diameter. This nodule is bordered by schreibersite and at one point by a small mass of graphite.

The two meteorites above described were analyzed by F. A. Gonyer with the results shown in the following table.

ANALYSES OF TWO METEORITE IRONS BY F. A. GONYER

1. Baquedano Meteorite, Chile
2. Deport Meteorite, Texas.

	1	2
	Per cent	Per cent
Fe	90.90	91.26
Ni	8.82	7.97
Co	0.15	0.41
Cu	0.03	none
Mn	absent	absent
P	0.24	0.12
S	0.05	none
Insoluble	0.01	0.37
	<hr/> 100.20	<hr/> 100.13
Sp. Gr.		7.67

The analyses of these irons show normal content in nickel and no unusual features. The low sulphur in No. 1 and its absence in No. 2 simply reflect the chance of sampling for pyrrhotite is present in both. The same may be said of phosphorus which does not show in either analysis in an amount comparable with the visible schreibersite in the sections.

Since the above was written two small masses of the Deport meteorite have been received at the Harvard Museum weighing respectively about six and two pounds. They add no new facts to the description of the meteorite.

MULTIPLE TWINS OF DIAMOND AND SPHALERITE

CHARLES PALACHE

Two twin groups in the Harvard Mineral Collection seem sufficiently different from any that have been described to be worthy of illustration.

The diamond multiple twin (No. 90303) is from South Africa. It is shown in fig. 1, from a photograph, with enlargement of about 6 diameters. The specimen is water white, weighs 1.8 carats and measures 8 mm. in greatest diameter and 5 mm. in thickness. The photograph is not sharp in the middle field so the actual appearance of the object is not brought out. It is wheel-like, the six spokes or teeth surrounding a central hub which projects about 2 mm. above and below the general plane of the wheel. The central crystal, like all the "radiating" ones, is seen in the direction of a trigonal axis and each is twinned about this axis or on the "spinel law." Any twin-pair is a much rounded dodecahedron much like figure 352 in Goldschmidt, *Atlas der Kryst.*, Vol. 3, Tafel 47, which is from Fersmann & Goldschmidt, *Diamant*, 1911, Plate 36, fig. 244. The faces are much too rounded to permit of ordinary crystal measurement, but the general character of the crystal form is unmistakable.

In order to explain diagrammatically the relations of the members of the group, there are shown in figure 2, models of seven spinel-twinned octahedrons grouped as it is quite certain the members of the diamond twin-aggregate are grouped. The central model (hub of the diamond wheel) No. 1 is parallel to numbers 2, 4, and 6. Nos. 3, 5, and 7 are parallel to each other but in twin relation to No. 1. Or we can say that the upper half of 1 is twinned to the lower halves of 2, 4, and 6 and the upper halves of 3, 5, and 7 while the lower half of 1 is twinned to the upper parts of 2, 4, and 6 and the bottoms of 3, 5, and 7. The spokes are evidently in twin position to next neighbors. Either two individuals or fourteen are then involved in this multiple twin, depending upon the point of view regarding such intergrowths of the individual observer.

The sphalerite twin (No. 91613) came to the Harvard Museum many years ago from the Cashier Mine near Breckenridge, Colorado. It is a tetrahedron of black color and good lustre, 3 cm. on an edge, with all four faces of the tetrahedron showing in whole or in large part. A view of this specimen is shown in fig. 3, which is from



FIG. 1. Photograph of diamond multiple twin viewed from the direction of a trigonal axis. Magnification about 9.



FIG. 2. Photograph of crystal models to explain twinning of diamond.

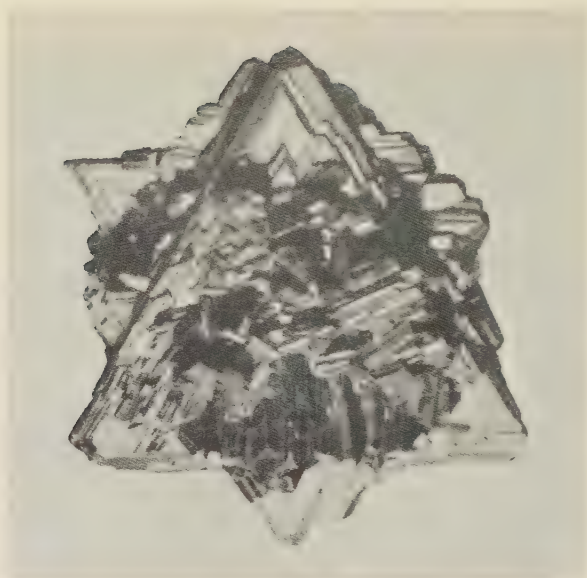


FIG. 3. Photograph of sphalerite multiple twin viewed from the direction of a trigonal axis. Magnification about $2\frac{1}{4}$. (Dr. W. T. Schaller, phot.)



FIG. 4. Same after coating the crystal with ammonium chloride to dull reflections from faces. (Dr. W. T. Schaller, phot.)

a photograph looking directly down on a tetrahedron face. Besides the dominant tetrahedron which may be regarded as the positive one there are small but very bright faces of the negative tetrahedron and faint lines of the cube on the long edges.

In the figure it is clear that the tetrahedron face with the base of its triangle horizontal is in twin position to the similar face visible only in its points; and that this twinning is about a trigonal axis. At the same time one can see on the tetrahedron face three groups of parallel ridges dipping down towards the centre of the aggregate. They are shown best, especially the least developed set, on fig. 4. These ridges are the cube edges of three sets of intergrown tetrahedrons, each of which bears to one of the remaining three faces of the tetrahedron the same twin relation as shown for one pair in the photograph. In other words this is a fiveling, with four crystals or groups of parallel crystals twinned about each of the four trigonal axes of the primitive tetrahedron. The individual sets of crystals are closely parallel as is shown by the almost simultaneous reflections from the bright negative tetrahedron faces when the face is turned to the right position. Each tetrahedron face of the "central" or primitive tetrahedron shows the same characters as above described for the face shown in the photograph.

I am indebted to Dr. W. T. Schaller for the excellent photographs shown here of the unusual twin group.

THE LARGEST CRYSTAL

CHARLES PALACHE

How large can crystals grow? What teacher of mineralogy but has been asked this question many times. He would probably reply that there is no limit but if he tried to tell of the biggest that had been found he would find it difficult to give an exact answer.

This is not an idle question. Large crystals of any substance imply not only abundance of their constituents but extraordinary concentration at one place and unusual constancy of conditions during long periods. The minerals that are often found in large crystals are at least in part composed of the less common elements so that the problem of concentration in time and place is doubly interesting and difficult. How do they support their own weight during growth and how maintain form and outline? Why is there such a varying maximum of size in different mineral species?

Whatever their interest and significance, large crystals would be more intelligible if we had more exact data as to their actual limits of size. I have myself made a very few observations of actual dimensions of crystal giants and would like to collect others. Will not every reader of this magazine supply such data as he possesses? I will make it a welcome duty to collate and publish the information. The more various the range of minerals included may prove to be the more valuable will be the information. Each case should carry with it such data as are available as to the place and kind of deposit where it was found. The information given below is in part derived from various publications. Where no author is quoted the data are from specimens in the Harvard Mineralogical Collection.

<i>Stibnite</i>	Japan.....	Crystals up to 60×5 cm.	Wada
<i>Galena</i>	Isle of Man.....	Cubes of 25 cm.	Greg and Lettsom
	Miss. Valley.....	Cube of 16 cm.	
<i>Pyrite</i>	Alaska.....	Cube of 13 cm.	
	Colorado.....	Cube 12½×10×14 cm.	
	Elba.....	Octahedron 15×15×23 cm.	
<i>Fluorite</i>	Cornwall.....	Cleavage octahedron 14 cm. on edge	
	Cumberland.....	Cube 13 cm. on edge	
	Jefferson Co., N.Y....	Cubes more than 30 cm.	Beck

<i>Calcite</i>	Iceland.....	Rhombohedron 6×2 meters	Des Cloizeaux
	Sterling Bush, N.Y....	Rhombohedron 109×95×46 cm. Weight about 1000 pounds	Whitlock Farrington
	Missouri.....	Scalenoedron 76 cm. long	
<i>Quartz</i>	Switzerland.....	Weight about 1400 pounds	Hintze
<i>Corundum</i>	Transvaal.....	61×30 cm. Weight 335 pounds	Hall
<i>Gahnite</i>	Sterling Hill, N.J....	Octahedron 12.5 cm. on edge	Canfield
<i>Franklinite</i>	Sterling Hill, N.J....	Octahedron 17.5 cm. on edge	Canfield
<i>Microcline</i>		No definite data	
	Maine.....	"up to 20 feet across" (6 meters)	Bastin
<i>Pyroxene</i>	Hybla-Ontario.....	Cleavage 16×16×40 cm.	
<i>Hornblende</i>	Sterling Hill, N.J....	15×15×46 cm.	
<i>Spodumene</i>	Etta Mine.....	42 feet by 5 feet 4 in. (12.7× 1.7 meters) Weight 90 tons	Ziegler
<i>Beryl</i>	Albany, Maine.....	18×4 feet (5.5×1.2 meters)	Gedney and Berman
		Weight 18 tons	
<i>Garnet</i>	Rogers Mine, North Creek, N.Y.....	Dodecahedrons up to 2 ft. (61 cm.) diameter	Miller
<i>Scapolite</i>	Templeton Tp., Quebec	23×25.5×35 cm. Weight 75 pounds	Parsons
<i>Zircon</i>	Brudenell Tp., Ontario.....	10×10×30 cm. Weight of 15 pounds	Parsons, Kunz
<i>Titanite</i>	Renfrew Co., Ont....	10×12×5 cm. twin	
<i>Mica</i> Phlogopite	Lacy Mine, Ontario..	14 feet diam. 33 ft. long (4.2× 9 meters) yielded 60 tons trimmed mica. (Estimated total weight not less than 90 tons)	Ellsworth
<i>Barite</i>	Dufton, England....	Weight 100 pounds	Greg and Lettsom
<i>Gypsum</i>	Chile, Braden Mine..	10 ft.×3 in. (3 meters×8 cm.)	Lindgren
	Utah, Wayne Co....	4 feet by 6 inches (1.2×.15 meters)	Talmage
	Mexico, Naica.....	5.5 feet by 5 inches (1.67×.13 meters)	Foshag

